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Maximum Utilization of Water Resources in a Planned Community

Stormwater Runoff Quality: Data Collection, Reduction and Analysis

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16. ABSTRACT

An ecologically planned community (The Woodlands, Texas) has adopted a unique water management plan designed to avoid adverse water quality and hydrological effects due to urbanization while benefiting from the existing natural drainage. The initial years of development were monitored by a comprehensive sampling and analytical program in an effort to evaluate the innovative new water resources concept. Data on water quantity and quality were collected during dry weather and during stormwater runoff. To supplement the prime study site, stormwater samples were also collected at watersheds in the Houston area. Parameters monitored during the reporting period were as follows: rainfall, streamflow, chemical oxygen demand (COD), soluble organic carbon (SOC), biochemical oxygen demand (BOD), ammonia (NH_3), nitrate (NO_3), nitrite (NO_2), total Kjeldahl nitrogen (TKN), orthophosphates (ortho-P), total phosphorus (TP), dissolved oxygen (DO) pH, turbidity, total suspended solids (TSS), and specific conductance.. Data were analyzed for water quality relationships in an effort to predict pollutant loads according to land use. Comparisons were made to wastewater and rainwater quality.

Significant relationships were observed between total volume of runoff and total load of various pollutants. The load-runoff relations are a function of the type of land use activity in the watershed and have been used to simulate stormwater quality responses.

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MAXIMUM UTILIZATION OF WATER RESOURCES IN A PLANNED COMMUNITY

Stormwater Runoff Quality: Data Collection, Reduction and Analysis

by

William G. Characklis, Frank J. Gaudet,
Frank L. Roe and Philip B. Bedient
Department of Environmental Science and Engineering
Rice University
Houston, Texas 77001

Grant No. 802433

Project Officers

Richard Field
Anthony N. Tafuri
Storm and Combined Sewer Section
Municipal Environmental Research Laboratory (Cincinnati)
Edison, New Jersey 08817

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and governmental concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimony to the deterioration of our natural environment. The complexity of that environment and the interplay between its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems for the prevention, treatment, and management of wastewater and solid and hazardous waste pollutant discharges from municipal and community sources, for the preservation and treatment of public drinking water supplied and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research; a most vital communications link between the researcher and the user community.

This project focuses on methods maximizing the use of water resources in a planned urban environment, while minimizing their degradation. Particular attention is being directed towards determining the biological, chemical, hydrological and physical characteristics of storm water runoff and its corresponding role in the urban water cycle.

Francis T. Mayo
Director
Municipal Environmental Research
Laboratory

PREFACE

The overall goal of this research was to evaluate the water resource plan for The Woodlands, Texas, and to make recommendations, as necessary, to maximize its effective utilization through alterations in design and management. Any recommended alterations were to be critically evaluated as to their compatibility with the natural environment.

Collection and utilization of stormwater runoff for recreational and aesthetic purposes was a major feature of the water resources plan at The Woodlands. Control of downstream flooding was also of great importance and so storage reservoirs, in the form of recreational lakes and wet weather ponds, were created by the developers. Water quality was a concern if the impoundments were to be aesthetically appealing and/or suitable for recreation. Therefore, a major sampling and analytical program was designed to monitor water quality and quantity at different locations in the developing area. The Storm Water Management Model (SWMM) provided the focal point for combining the water quality and quantity data into a predictive tool for design and management purposes.

SWMM was originally developed for highly urbanized areas and, therefore, was calibrated for this project in an urban watershed (Hunting Bayou). Subsequently, SWMM was modified to model runoff and water quality from natural drainage areas, such as The Woodlands. Because of the lag in the construction schedule at The Woodlands, the dense urban areas were not completed during the project period. Consequently, Hunting Bayou and other urban watersheds were sampled to provide a basis for predicting pollutant loads at The Woodlands in the fully developed state.

Water analyses included many traditional physical, chemical and biological parameters used in water quality surveys. Pathogenic bacteria were also enumerated since the role of traditional bacterial indicators in stormwater runoff was not clear. Algal bioassay tests on stormwater were conducted to assess the eutrophication potential that would exist in the stormwater impoundments. The source, transport and fate of chlorinated hydrocarbons in stormwater runoff was also investigated.

Several of the large Woodlands impoundments will receive reclaimed wastewater as the major input during dry weather. Besides their use as a source of irrigation water, the lakes will be used for non-contact recreation -- primarily fishing and boating. Because the reclaimed wastewater must be disinfected, there was a concern about disinfectant toxicity to the aquatic life in the lakes. Consequently, comparative fish toxicity tests were conducted with ozone and chlorine, the two alternatives available at the water reclamation plant.

Porous pavement was considered by the developers as a method for reducing excessive runoff due to urbanization and an experimental parking lot was constructed. Hydraulic data was collected and used to develop a model compatible with SWMM, to predict the effects of using porous pavement in development. Water quality changes due to infiltration through the paving were also determined.

Hopefully, the results of this project will contribute in a positive way to the development of techniques to utilize our urban water resources in a manner more compatible with our cherished natural environment.

ABSTRACT

An ecologically planned community (The Woodlands, Texas) has adopted a unique water management plan designed to avoid adverse water quality and hydrological effects due to urbanization while benefiting from the existing natural drainage. The initial years of development were monitored by a comprehensive sampling and analytical program in an effort to evaluate the innovative new water resources concept. Data on water quantity and quality were collected during dry weather and during stormwater runoff. To supplement the prime study site, stormwater samples were also collected at watersheds in the Houston area. Parameters monitored during the reporting period were as follows: rainfall, streamflow, chemical oxygen demand (COD), soluble organic carbon (SOC), biochemical oxygen demand (BOD), ammonia (NH_3), nitrate (NO_3), nitrite (NO_2), total Kjeldahl nitrogen (TKN), orthophosphates (ortho-P), total phosphorus (TP), dissolved oxygen (DO), pH, turbidity, total suspended solids (TSS), and specific conductance. Data were analyzed for water quality relationships in an effort to predict pollutant loads according to land use. Comparisons were made to wastewater and rainwater quality.

Significant relationships were observed between total volume of runoff and total load of various pollutants. The load-runoff relations are a function of the type of land use activity in the watershed and have been used to simulate stormwater quality responses.

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LIST OF ABBREVIATIONS

BOD	Biochemical Oxygen Demand
COD	Chemical Oxygen Demand
DO	Dissolved Oxygen
g	mass flow rate
HB	Hunting Bayou watershed
ortho P	Orthophosphate
P	mass of pollutant
PDS	slope of the load-runoff curve at some point in time
PVC	Polyvinyl Chloride
Q	volumetric flow rate
r	rate of runoff
S	total storage
SOC	Soluble Organic Carbon
SWMM	EPA Stormwater Management Model
TKN	Total Kjeldahl Nitrogen
TOC	Total Organic Carbon
TP	Total Phosphate
TSS	Total Suspended Solids
WB	Westbury watershed

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W. L. Lloyd
K. Manchen
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L. P. Metzgar
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J. B. Smith
C. Stagg
M. Walker
C. H. Ward
J. C. Weismiller
L. Wong
A. Yarletts
J. S. Zogorski

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D. Casserly
E. M. Davis
J. Greene
P. Mattox
P. Mittlemark
D. Moore
H. Tamashiro

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E. Diniz
D. Holloway
T. Remaley
F. Sofka
D. E. Winslow

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SECTION 1

INTRODUCTION

Surface waters are maintained at a desirable natural quality standard through the control of pollutant discharges. Historically, abatement procedures have focused upon control of industrial and municipal effluents, the point sources. Increasingly stringent point source effluent standards have generated concern for non-point source pollution control. Urban stormwater runoff is considered a major problem in this regard.

The hydrological characteristics of natural watersheds change with urbanization. Replacement of flow-retarding vegetation with impervious surfaces, such as roads and buildings, increases the amount of stormwater runoff. Removal of the water is traditionally implemented by the use of an urban drainage system consisting of storm sewers and deep, concrete-lined drainage ditches, designed specifically for prompt drainage. Increased runoff volumes and peak flow rates result, creating problems of downstream flooding and channel erosion.

Infiltration of stormwater is a major groundwater recharge source, however the urban emphasis of surface removal minimizes the infiltration rate, resulting in a lowered water table and possible urban land subsidence problems. Water quality in the area becomes generally poorer because the natural purification which infiltration provides is compromised.

The urban environment typified by industry, highways, solid waste and high population density provides a major pollutant source for runoff waters (1). Recent investigations recognize the significance and magnitude of pollution problems from urban stormwater runoff. In terms of specific pollutants, the sediment yield problem is the most dramatic. Due primarily to urban construction, urban sediment loads were found to be as much as 75 times greater than loads in agricultural regions (2, 3). Other runoff pollutants reported higher in urban regions include dissolved solids (4), coliforms (5), biochemical oxygen demand and chemical oxygen demand (BOD and COD) (6), polychlorinated biphenyls, heavy metals, pesticides and fertilizers (6-9). To verify these findings, the present study proposed to monitor urban development activities and define stormwater pollution characteristics.

SECTION 2

CONCLUSIONS

Stormwater runoff from an undeveloped forested watershed is relatively low in pollutants and pollutant indicators. Typical values are: Total Phosphorous (TP) 0.06 mg/l, Total Kjehdahl Nitrogen (TKN) 1.24 mg/l, Total Suspended Solids (TSS) 36 mg/l, Total Chemical Oxygen Demand (COD) 42 mg/l, and Dissolved Oxygen (DO) 6 mg/l.

Development in the forested watershed has significantly increased TSS and nutrients in runoff. COD and other organic parameters were not affected. Increased TSS values are a result of sediments washed from construction sites, some located within the floodplain. Development of The Woodlands area will increase surface water turbidity. Dredging will probably be necessary to remove excess sediments from lakes and ponds. Increased nutrient loads from developed areas will create algal and macrophyte growth problems in The Woodlands lake system.

Houston urban runoff contains higher nutrient and TSS loads than forest runoff. Nutrient concentrations (ammonia, TKN, nitrate, nitrite, TP, ortho phosphates) are as much as 10 times greater in urban areas. TSS concentrations are 4 times greater. Higher concentrations combined with increased runoff coefficients (the amount of runoff for a given amount of rainfall) provide receiving waters with heavy pollutant loads in urban areas. Sediment buildup and algal growth problems will result in impoundments receiving such flows.

A man-made lake serves as an effective trap for excessive sediments transported by construction site runoff. During seven separate storm events totaling 10.2 inches (26 cm) of rainfall, 180 tons (1.6×10^5 kg) of sediment entering 110 ac-ft (13.56 ha-m) Lake Harrison was reduced to 34 tons (3.08×10^4 kg) in the effluent. This was an 81% reduction in sediment load.

A definite first flush was observed for urban and undeveloped watershed runoff, most commonly for TSS and turbidity parameters. The flush is related to transport of stream bed sediments. Urban drainage systems have increased transport potential and therefore exhibit higher flush concentrations.

Rainwater contain phosphates, nitrogen and COD which account for a significant portion of runoff pollutant loads.

Natural soils are capable of removing nutrients found in rainwater. Disturbed soils in developing areas lose this capability.

Municipal wastewater would require advanced treatment to meet nitrogen and phosphorus concentrations in stormwater runoff. Secondary treatment of wastewater will lower suspended solids and COD concentrations below that in stormwater runoff.

A linear relationship exists between total pollutant loads and total stormwater runoff which is useful in comparisons between watersheds and analytical prediction of stormwater pollutant loads.

A statistical ranking of four watersheds, on a lb/ac/in (kg/ha/cm) of runoff basis, indicates that urban watersheds are clearly the greatest producers of TSS and nutrient loads. Loads from the forested and developing watersheds are lower by as much as an order of magnitude.

The load-runoff curves may be used to sequentially simulate mass flow curves. Simulation of a six month period, containing three measured storm events, produced reasonable comparisons of observed and simulated curves.

Stormwater treatment at The Woodlands should be restricted to sedimentation in the man-made lakes. Costs prohibit the construction of facilities which would result in no significant effect on the use of lakes.

Stormwater sample preservation in battery operated samplers by ice refrigeration is not feasible.

Representative sampling of TSS (with high clay content) by automatic samplers was excellent.

Recording monitors (pH, DO, temperature and turbidity) require weekly maintenance for recalibration and antifouling measures.

Cross-sectional homogeneity of stream parameters should be verified before choosing stream sampling points.

Discharge proportional sampling is an efficient method leading to characterization of stormwater runoff.

Glass fiber filters were not suitable for removing fine or coloidal particles from natural water samples.

Refrigeration plus mercuric chloride preservation was not adequate for stabilization of ortho-phosphate (ortho-P) at low levels in surface water samples.

SECTION 3

RECOMMENDATIONS

Continued research at The Woodlands is needed to assess its planned water resources system. These studies should be conducted at a future date when development is more advanced.

Research is needed to establish the relationship of air pollution to rainwater and runoff quality. Special attention should be focused on the water quality effects of projected ambient air criteria.

Sediment discharge from construction area stormwater runoff should be controlled. Suggested methods are:

1. Prevention; i.e., prohibiting construction in flood plain areas.
2. Treatment; i.e., by sedimentation basins or more sophisticated methods.
3. Control of erosion by various techniques.

More stormwater quality data should be obtained on Hunting Bayou and Westbury watershed so that unit loadographs can be simulated for single storm events. Investigations can then determine relationships between the gamma distribution shape parameters (n, k) and land use or physiographic factors in the watershed.

Simpler methods for determining annual loads, partially developed during this research, should be refined and verified with field data. The methods show great promise for differentiating between point source and non-point source pollution loads.

Automatic discrete sampling of streams is most efficiently carried out by a high speed (2 ft/sec or 60 cm/sec) peristaltic or vacuum chamber type, battery operated sampler such as Isco, Manning or Sirco models. Some mechanical and electronic malfunctioning was encountered with the Manning S-4000 sampler.

Sample filtration through Millipore HATF membrane filters was adequate, however, Nucleopore membrane filters should be used due to the added advantage of low tare weight and a hydrophobic response allowing rapid drying to constant weight.

Analyses of TKN, TP and COD on refractory compounds by the Technicon automated methods (helical digestor for TKN and TP and digestion bath for COD) were inferior to manual methods because of incomplete digestion.

Efficiency of pumping in Sigmamotor samplers is improved by replacing existing pumping mechanism with a "Masterflex" pumphead.

Better field preservation methods for discrete samples should be developed.

SECTION 4

SITE DESCRIPTIONS

Several sites in the Houston metropolitan area were chosen to determine if stormwater runoff quality is dependent on land use and development activities. The primary study site is The Woodlands, Texas, a planned satellite city selected for a comprehensive investigation of runoff quality during all phases of development. Two other watersheds were chosen to supplement data collected from The Woodlands. Hunting Bayou is a developed watershed with strong industrial influences and deteriorating residential areas. Westbury Square is a middle class residential area chosen because of the absence of construction in the watershed. The locations of these study sites are shown in Figure 1. Each watershed is comprehensively described in the following text.

THE WOODLANDS

General Description

The Woodlands is a newly planned community being developed in southern Montgomery County, Texas. The community is situated in a heavily forested tract about 35 miles (56 km) north of Houston, directly west of Interstate 45 (see Figure 1). The Woodlands encompasses 17,776 acres (7194 ha) and will be developed over a twenty-year period beginning September, 1972. In contrast to a residential subdivision, The Woodlands will contain all services of a modern city, including facilities for social, recreational, educational, commercial, institutional, business and industrial pursuits. The community concept is committed to high standards for environmental and lifestyle quality. The phased, long range development places priority on ecological preservation and balance, as well as social and habitational quality. This objective is to be accomplished through a comprehensive environmental preservation and management program, including planning and design controls. The water resource system in The Woodlands, including its drainage system, is a good example of such planning and was the primary subject of this research.

Development Plan

The prime objective of The Woodlands is to provide the finest urban environment in the Houston metropolitan area in

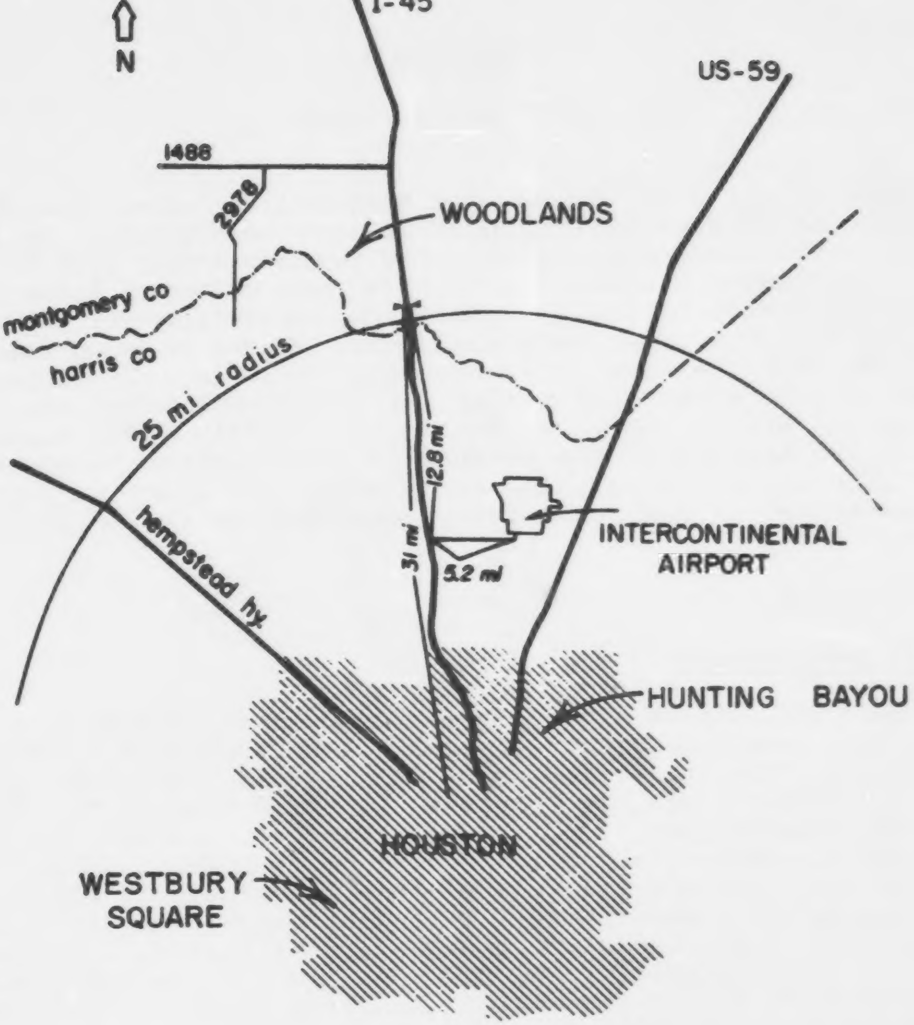
I-45
N
US-59
1488
2978
WOODLANDS
montgomery co
harris co
25 mi radius
12.8 mi
31 mi
5.2 mi
INTERCONTINENTAL AIRPORT
hempstead hy.
HUNTING BAYOU
HOUSTON
WESTBURY SQUARE

Figure 1. Location of study sites.
1 mi = 1.6 km

terms of physical setting and quality of human life and community services. The basis for all aspects of development in The Woodlands is a unique ecological inventory conducted from 1971-1973. The geology, soils, drainage, water resources, weather, vegetation, and wildlife endemic to The Woodlands were evaluated by specialists. The findings of these studies were the basis for developing criteria to locate roads, homes, offices, and other physical structures to be built at The Woodlands.

A summary of the land use allocation for The Woodlands is shown in Table 1. Residential areas will occupy 6,820 acres (2,760 ha) of The Woodlands site. A total of 33,000 dwelling units are programmed. Housing units planned include single family detached, townhouses and patio, and apartments. The projected population in 1992 is 112,000. Another 1,699 acres (688 ha) is being designated for restricted industrial use. Additional area has been allocated for retail, commercial, office, open space, and other land sales. Approximately one-third (30.2%) of The Woodlands has been designated open space. The majority of this space will be located within the floodplain of Panther Branch and its major tributary, Bear Branch.

The Revised General Plan for The Woodlands includes all of those elements essential to modern living. Social, recreational, educational, commercial, institutional, business, cultural and industrial elements are planned within The Woodlands. A concern for nature and convenience for man were two of the major criteria used in the development of the General Plan for The Woodlands.

Climate

The macroclimate of the Houston metropolitan area is dominated by the Gulf of Mexico. Winters in the region are normally mild, while summers are hot and humid. The mean daily winter temperature is about 50° F (10° C), whereas the mean daily summer temperature is 82° F (27.8° C). The average maximum daily temperature is 97° F (36° C) and occurs in August. The average minimum daily temperature is 38° (3.3° C) and occurs in January. Freezing temperatures occur about seven days per year. Figure 2 summarizes the variation of ambient temperature for the Spring Creek basin, in which The Woodlands is located.

Average yearly rainfall in The Woodlands totals about 46 in (117 cm) and is evenly distributed throughout the year. Annual extremes range from 17.66 in (44.86 cm) in 1900 to 77.43 in (196.67 cm) in 1973. However, a majority of years of record (75%) have recorded annual rainfall between 30 and 60 in (76 and 152 cm). April, May, November and December are usually the wettest months, while March is the driest month. The areal variation of rainfall for specific storm events can be significant especially during summer months. The majority of rainfall occurring during June, July, August and September is associated

TABLE 1. SUMMARY OF LAND USE ALLOCATION FOR THE WOODLANDS

General Breakdown	1 ac = .405 ha Acres	Percent
Residential	6,820	38.4
Retail and Commercial	470	2.6
Office	724	1.5
Industrial (including roads)	1,699	9.6
Open Space	7,803	43.9
Other		
- phase one*	276	1.6
- health	39	.2
- churches	72	.4
- schools	322	1.8
	17,776	100.0
Open Space (developed uses)		
University	350	2.0
Protective Services	22	.1
Neighborhood, mini, playlot	90	.5
District Parks	90	.5
Community Center Library	16	.1
Village Centers	19	.1
Pathway	354	2.0
Townwide Road	990	5.5
Golf (public)	300	1.7
Golf (private)	200	1.1
Equestrian Center	10	.1
	2,441	13.7
Open Space (undeveloped uses)		
Floodways	3,635	20.4
Drainage	1,328	7.5
Wildlife Corridors	175	1.0
Miscellaneous	225	1.3
	5,363	30.2

*Initial development - Conference Center, model residential areas, and office buildings.

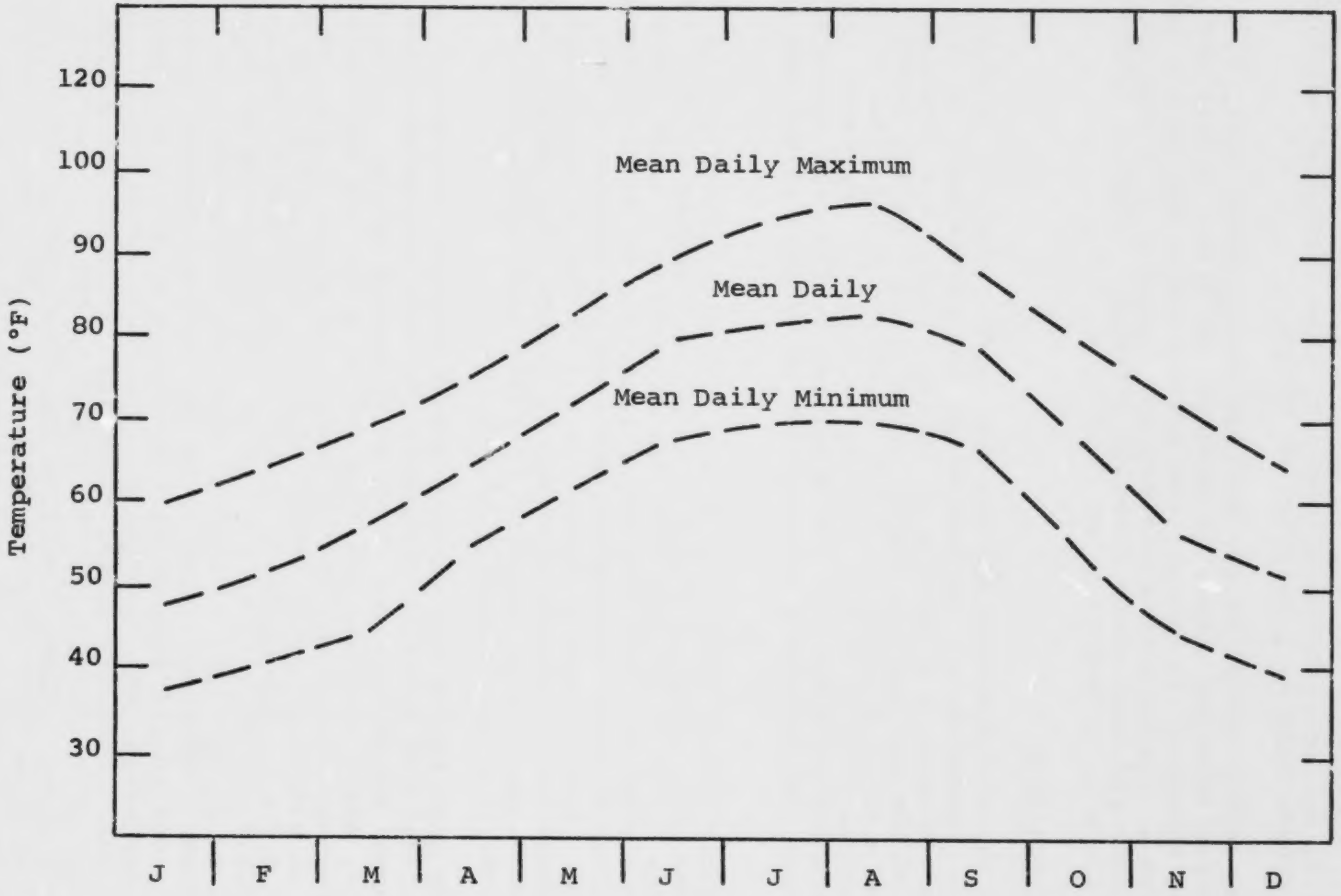

Figure 2. Average monthly air temperatures at Conroe, Texas. $^{o}F = 9/5^{o}C + 32$

with thunderstorms. Precipitation during these months is unpredictable. Frequently an inch or more (a few centimeters or more) of rainfall can be recorded in one part of a watershed, while a short distance away no precipitation occurs.

Snow rarely occurs in the Houston metropolitan area, although three separate snowfalls occurred in 1972. Prevailing winds are northerly in January and southeasterly during the rest of the year. Destructive winds are not frequent, although excessive rain and high winds normally accompany tropical depressions which move inland from the Gulf of Mexico.

Existing Drainage

The natural drainage for The Woodlands community is shown in Figure 3. Approximately 80 percent of the development is drained by Panther Branch, a tributary of Spring Creek. The remaining portion of the development drains directly into Spring Creek, which has a total drainage area of 750 square miles (1942.5 sq. km). Because Panther Branch and its tributaries represent the major existing drainage for the development site, the hydrologic, morphologic and transport characteristics of this stream are important.

Panther Branch is approximately 14.6 miles (23.5 km) in length and has a total drainage area of 36.2 square miles. It originates north of FM road 1488 and travels in a south southeasterly direction. The only major tributary to Panther Branch is Bear Branch, which drains the northwestern portion of the watershed. Bear Branch is 9.0 miles (14.48 km) in length and drains about 42% of the Panther Branch basin. The headwaters of Bear Branch are located north of FM 1488, near Egypt, Texas, and water flows in a southeasterly direction.

Both Bear Branch and Panther Branch meander extensively and have well-defined low-flow channels. Representative examples of the streams' morphology are shown in Figures 4 and 5. Alluvial sediments, small riffles, and slow moving pools are commonplace within Panther Branch and Bear Branch. The width of the low flow channel is highly variable but is normally between 5 and 20 feet (1.5 and 6.1 m). The depth of the established channel increases from about 2 to 4ft (.61 to 1.22 m) in the headwaters to approximately 8 to 12 ft (2.44 to 4.88 m) near the confluence with Spring Creek. When the capacity of the defined channel is exceeded, storm runoff discharges into a very broad, flat floodplain. Presently, the floodplain has a heavy brush cover. The width of the floodplain varies along the length of the stream but is typically 1000 to 2000 ft (304.8 to 609.6 m) for a 100 year storm event. Flood runoff is characterized by low velocities and shallow depth because (a) a large land area is inundated, (b) flow resistance is high and (c) hydraulic slope is low. Excluding those areas presently under construction, essentially

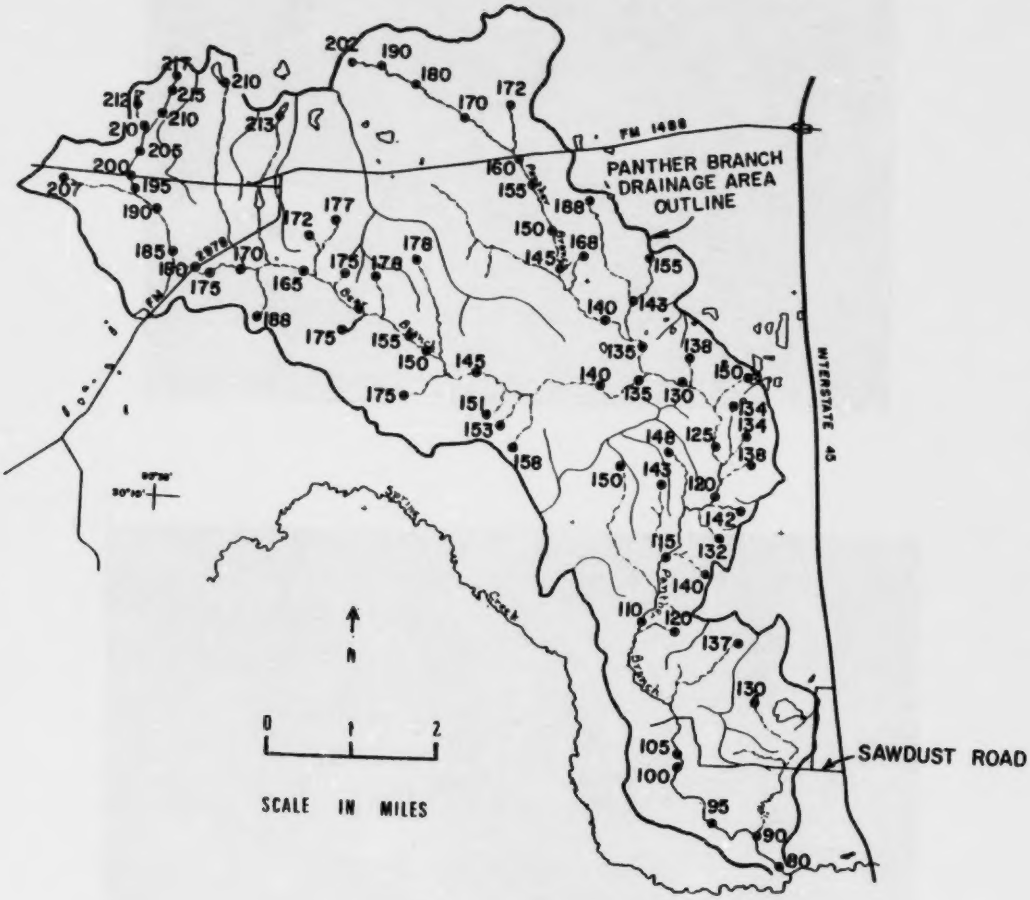
PANTHER BRANCH DRAINAGE AREA OUTLINE
FM 1488
INTERSTATE 45
SAWDUST ROAD
FM 2978
Spring Creek
Bear Branch
Panther Branch
N
0
1
2
SCALE IN MILES
217
212
215
210
210
210
205
213
200
207
195
190
185
180
175
170
188
165
172
177
175
178
178
175
155
150
145
175
151
153
158
202
190
180
170
172
160
155
150
145
188
168
155
140
143
135
138
150
140
135
130
134
134
125
138
148
143
150
120
142
115
132
140
110
120
137
130
105
100
95
90
80

Figure 3. Existing drainage network for The Woodlands (numbers shown indicate elevation above mean sea level).

1 mi = 1.6 km

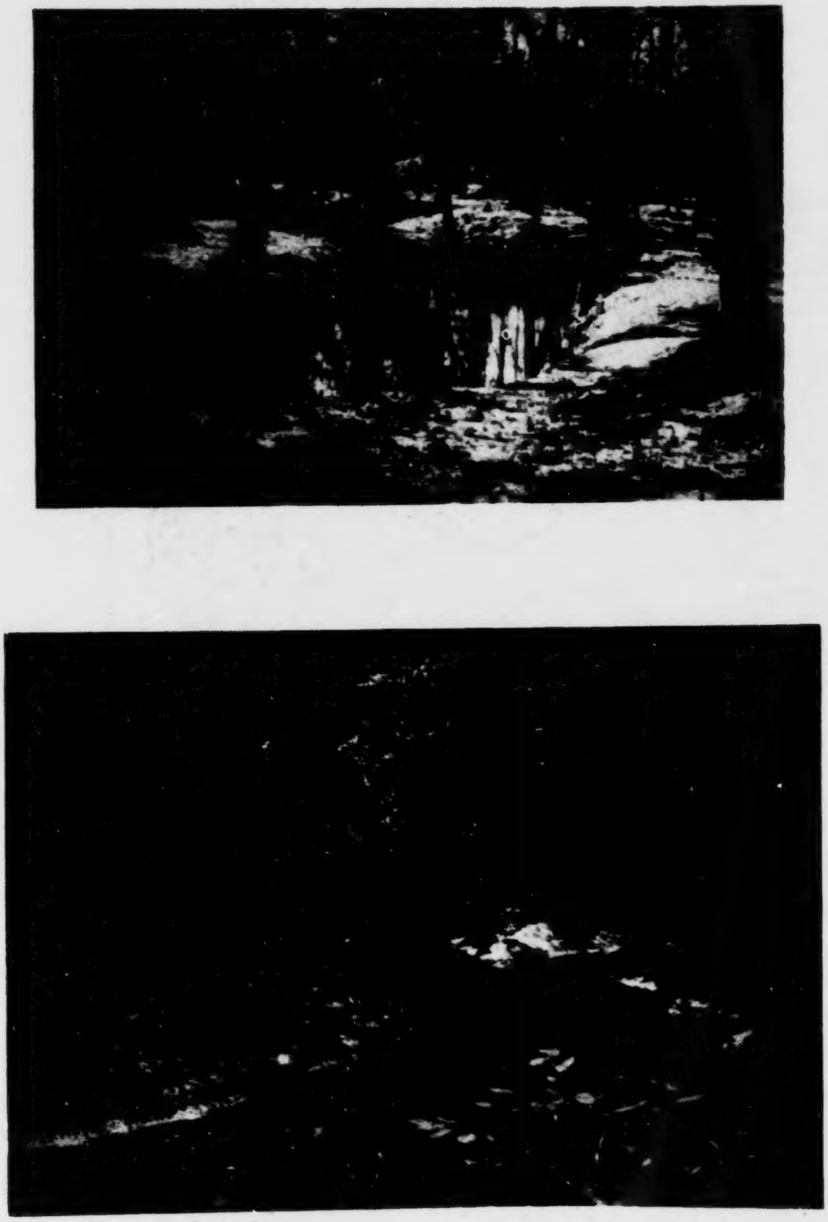

Figure 4. Panther Branch near confluence with Bear Branch.

Figure 5. Panther Branch near confluence with Spring Creek.

no evidence of any serious erosion can be found anywhere in Panther Branch watershed.

Time of travel measurements within the Panther Branch watershed yielded the asymptotic curve relationship presented in Figure 6. The relationship between travel time and discharge was developed for a 6.8 miles (10.9 km) reach of Panther Branch using fluorescent dye studies during low flow and time for hydrograph passage during storm runoff. Dye studies indicate water velocities below 0.1 ft/sec (.03 m/sec) are typical for dry weather flow. Consequently it is estimated that during low-flow conditions approximately 10 to 14 days of travel time is required for an element of water originating in the headwaters of Panther Branch to reach Spring Creek. The long travel time is a direct consequence of low channel slopes present throughout the drainage network. The elevation of the bottom of the stream channel above mean sea level for Panther Branch, Bear Branch and their tributaries is shown in Figure 3. Table 2 summarizes the change in elevation and slope for several stream reaches. The total change in channel elevation across the drainage basin is about 120 ft (37 m), with an average rate of change of 8.2 feet/mile (1.6 m/km) (0.16%). The slopes reported were calculated using river mileages delineated from USGS topographic maps (scale 1:23,000), however this technique normally underestimates the actual length of stream, especially when considerable stream meandering is present. The actual slope of Panther Branch is, therefore, more nearly 5 to 7 feet/mile (.95 to 1.33 m/cm).

Higher velocities of stormwater flow permit shorter travel times through the watershed. The hydrograph crest of a large storm event, flow greater than 100 cfs (2.8 m^3/sec) will traverse the watershed in less than 24 hours with surface water velocities approaching 1 ft/sec (.31 m/sec).

The impact of low channel and land slopes within The Woodlands is reflected in a relatively low surface runoff coefficient. U.S. Geological Survey data for the 1973 and 1974 water years show that only 23% of total rainfall ended up as surface runoff. The remaining 77% either evaporated, transpired or infiltrated into the ground. It should be noted that rainfall was heavy during the 1973 and 1974 water years, respectively 77 in (195.6 cm) and 51 in (129.5 cm). Thus it is estimated that only 10-15% of rainfall will run off during a year of average rainfall, 45 in (114.3 cm) (14).

Runoff from the Panther Branch watershed is not evenly distributed throughout the year. During the summer months of May through September little discharge occurs, except immediately following an intense and prolonged rainfall. The average daily low-flow discharge at Sawdust Road, including summer months, is 1 to 2 cfs (.03 to .06 m^3/sec). An average daily discharge of 100 cfs (2.8 m^3/sec) at this site is exceeded approximately 5% of the time.

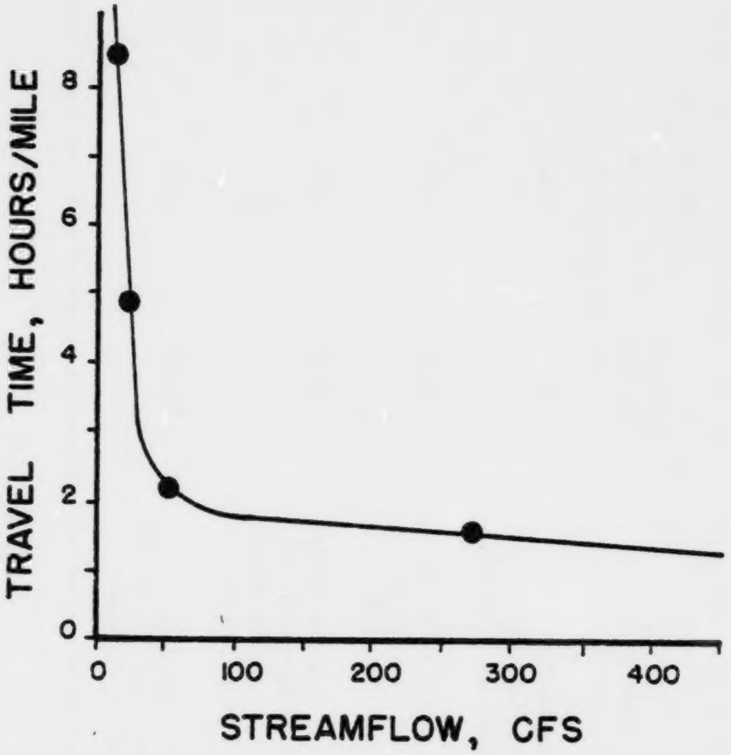

Figure 6. Panther Branch travel time discharge relationship.
1 mi = 1.6 km
1 cfs = .0283 m^3/sec

TABLE 2. SLOPE CHARACTERISTICS OF BEAR AND PANTHER BRANCHES

River	Reach	Length miles	Change in elevation feet	Slope of Channel feet/mile	Slope of Channel %
Bear Branch	Headwaters to confluence with Panther Branch	8.9	84	9.4	0.18
Panther Branch	Headwaters to confluence with Bear Branch	5.6	69	12.3	0.23
Panther Branch	Confluence with Bear Branch to confluence with Spring Creek	9.0	51	5.7	0.11
Panther Branch	Headwaters to confluence with Spring Creek	14.6	120	8.2	0.16

1 mi = 1.6 km

1 ft = .305 m

WATER RESOURCE SYSTEM OF THE WOODLANDS

An approximate water balance for The Woodlands is presented schematically in Figure 7. The annual rainfall at The Woodlands is partitioned as runoff into existing lakes and streams and infiltration into the ground. Losses result from evapotranspiration, evaporation and subsurface transport to streams.

The maintenance of a satisfactory groundwater reservoir above the perched water table is critical for the continued growth of vegetation. Any drainage system for The Woodlands must consider the detrimental consequences of disrupting the movement of water within this shallow aquifer. Deeper aquifers (1800 ft or 549 m) are used for community water supply.

A series of wet weather ponds and variable volume lakes will serve as recreational centers, wildlife preserves and, more importantly, storage of stormwater runoff. This system of waterbodies also contributes to the maintenance of an adequate perched water table for plant life. Lake water will be lost primarily through surface evaporation and irrigation. Inflow to the lake system will result primarily from stormwater runoff and reclaimed wastewater (approximately 20 mgd or .88 m^3/sec). If necessary, treated sewage effluents can be discharged directly into Panther Branch.

"Natural Drainage System"

The Woodlands Development Corporation has specified that the basic drainage system for their new community will utilize "natural drainage" concepts. Related design principles have been reported (15) and will not be described in detail herein. Rather, a brief summary is presented on the "natural drainage" concept and reasons for its selection in The Woodlands.

The normal procedure for disposing of stormwater runoff within the Houston Metropolitan Area is to enlarge the natural drainageways by deepening and widening existing stream channels and providing supplementary lateral drains. In the City of Houston, this approach generally results in storm sewers for the lateral drainage and deep, wide, concrete-lined ditches for the major drainage. This solution to stormwater disposal, although widely used and approved by the City of Houston, was incompatible with one of the major criteria used in developing The Woodlands--preserving and enhancing the natural environment. "Natural drainge" concepts adopted by Woodlands Development Corporation are envisioned as a method of providing adequate drainage and yet minimizing disruption of natural processes. Primary objectives of the drainage approach are to impede movement of surface runoff and to recharge stormwater runoff into the ground where feasible. Impediment and storage are provided by modifying existing drainageways, where necessary, with wide shallow swales, check dams, storage lakes and wet weather ponds. In comparison with the

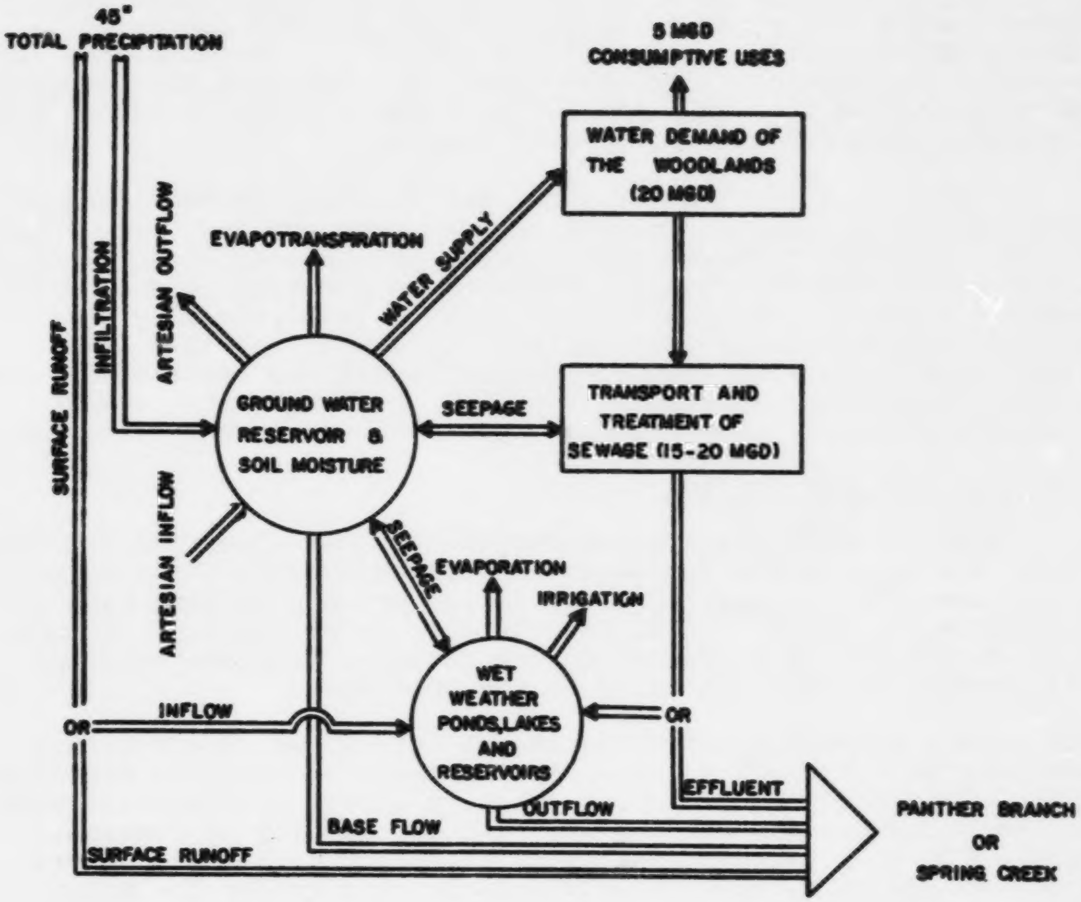
45"
TOTAL PRECIPITATION
5 MGD
CONSUMPTIVE USES
WATER DEMAND OF THE WOODLANDS (20 MGD)
EVAPOTRANSPIRATION
WATER SUPPLY
SURFACE RUNOFF
INFILTRATION
ARTESIAN OUTFLOW
GROUND WATER RESERVOIR & SOIL MOISTURE
SEEPAGE
TRANSPORT AND TREATMENT OF SEWAGE (15-20 MGD)
ARTESIAN INFLOW
SEEPAGE
EVAPORATION
IRRIGATION
WET WEATHER PONDS, LAKES AND RESERVOIRS
OR
INFLOW
OR
EFFLUENT
OUTFLOW
BASE FLOW
SURFACE RUNOFF
PANTHER BRANCH OR SPRING CREEK

Figure 7. Schematic water balance for The Woodlands.

normal approach, benefits of the "natural drainage" approach in managing stormwater runoff are as follows: (a) maximizes recharge, (b) minimizes runoff, (c) minimizes erosion and siltation problems, (d) minimizes vegetation removal and (e) minimizes cost of the drainage system. The "natural drainage" concept is essentially a recharge and containment approach to managing stormwater runoff and is designed to achieve the following goals: (a) reduce legal entanglements resulting from excessive runoff leaving the property, (b) sustain existing plant life by retention of a stable, high water table, (c) sustain planned perennial lakes and (d) minimize clearing and grading costs for swale and storm sewer trenching.

CLC LAKE SYSTEM

The man-made lake system at The Woodlands Commercial, Leisure and Conference Center (CLC) was filled during March 1974. The system, known as Harrison Lake, is comprised of two lakes separated by a decorative waterfall. The upstream smaller lake, designated Lake B, is constant volume. In dry weather there is no streamflow into the lakes, and the water level of Lake B is maintained by recirculating water from the lower lake, Lake A, or by the inflow of tertiary treated sewage. Sewage flow from the first phase of The Woodlands community is not uet a major source of lake water, however, projected sewage flow from Phase I is 6 mgd (.26 m3/sec). During wet weather, Lake B is designed to receive stormwater runoff and serve as a sedimentation basin for the 337 acre (136.4 ha) watershed under construction at this time. Upon completion, it will include an 18 hole golf course meandering through a residential area.

Lake A is a variable volume lake to be used for non-contact recreation. Lake dishcarge is controlled by an outlet box at an elevation of 121.8 ft (37.1 m) above sea level. Water from Lake A irrigates The Woodlands Golf Course bordering the lake's eastern and northern shores. In dry weather, the water level drops due to evaporation and grounwater is pumped into the lake to compensate. A clay bottom serves as an effective seal so that water is not lost to groundwater recharge.

HUNTING BAYOU WATERSHED

The Hunting Bayou watershed is located in Northeast Houston near the intersection of Highways 59 and 610. The 1,976 acre (800 ha) watershed is characterized by low land slopes and impermeable soils with high clay content. Primary drainage channels are trapezoidal in shape and lined with vegetation which varies in dnesity from moderate to very heavy depending upon the season and maintenance schedules. Typical channel conditions are showns in Figure 8. The majority of the secondary drainage is

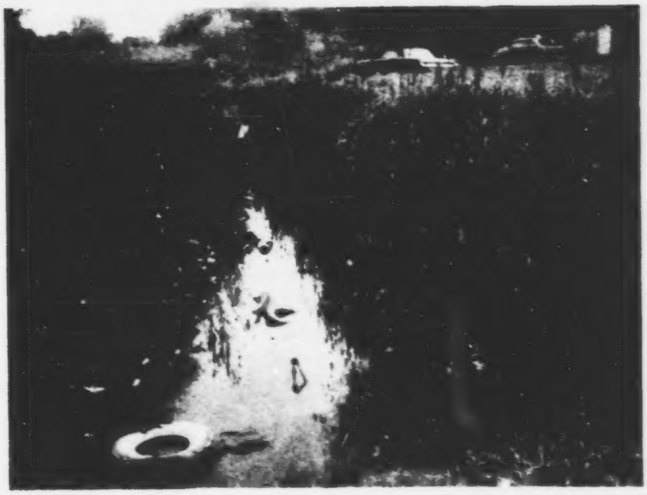

Figure 8. Photographs of typical channel conditions for Hunting Bayou.

provided by roadside, grass-lined swales (Figure 9) comparable to the drainage design at The Woodlands. A fourth of the area is drained by storm sewers. There are no known effluents entering the drainage system, however, point sources are probable due to the age of the residential districts (illicit sanitary sewer connections to the storm system and the presence of industrial influences). The area is poorly maintained and stream channels are sometimes used as dumping areas for waste materials such as oil and grease, old tires, and other refuse.

Land use in the watershed is mixed (Figure 10) with residential areas comprising the largest segment. Residences are mostly single family dwellings of low value. Table 3 gives demographic information regarding the indigent population.

Industrial activity in the watershed includes meat packing and rendering plants, wrecking yards and mechanical contractors. Various commercial establishments in the watershed support the residential population. Construction in the watershed is centered around completion of Interstate Highway 610.

WESTBURY SQUARE WATERSHED

The "natural drainage" system utilized by The Woodlands is an innovative method for controlling stormwater runoff and preventing water quality deterioration. A Houston watershed with a conventional drainage system was selected as a comparative study site. The residential land use of Westbury is similar to that being constructed at The Woodlands.

The 210 acre (85 ha) watershed is located in Southwest Houston and is comprised exclusively of single-family residential dwellings. No commercial or industrial influences are present in this area. The watershed is completely developed and contains no construction sites, empty lots, and no undeveloped land. Figure 11 and Table 4 provide watershed information.

Demographic information from the 1970 census presents the area as upper-middle class, median annual income of $19,000. Population density is approximately 11 persons/acre (27 persons/ha), or 4 persons/household.

The separate stormwater drainage system consists of lateral drainage provided by concrete pipe, 18 to 54 in. (45.7 to 137.2 cm) diameter, connecting with a main collecting channel at roadway intersections. The channel is an open grasslined ditch, often choked with vegetation in the summer months. The ditch passes through culverts beneath roadways, and at these points ponding occurs upstream and downstream providing slight storage of runoff and a reduction of flow velocity. Low runoff coefficients can be expected due to the low land slope of only 0.8%. Impervious cover is estimated at 35.4%. No dry weather flow is present in this watershed.

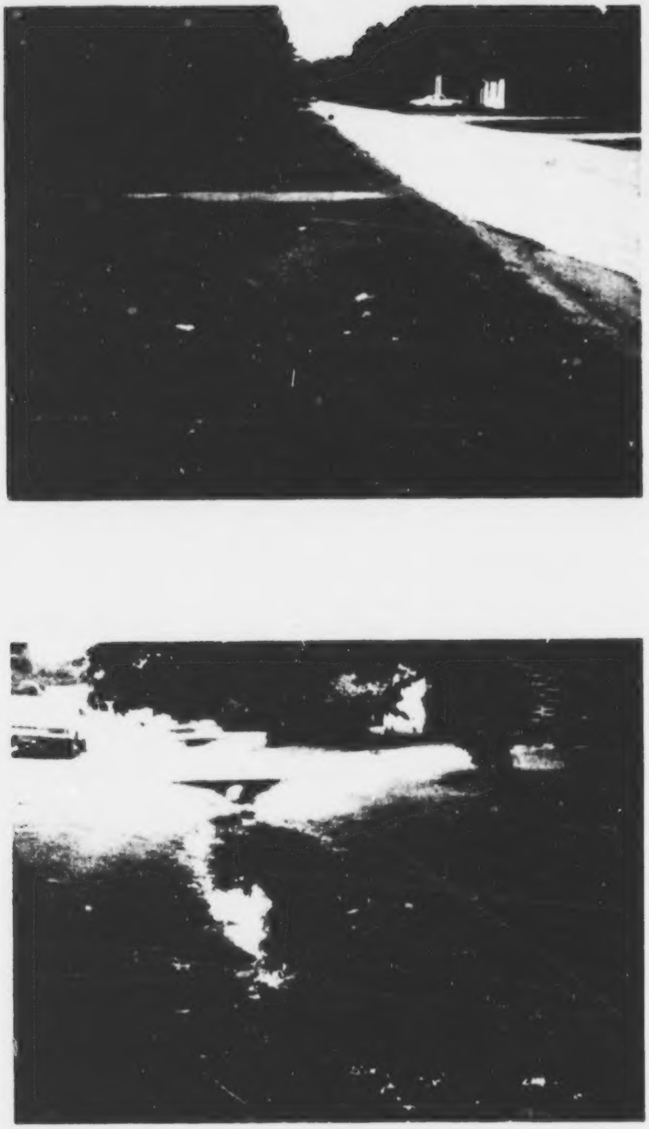

Figure 9. Photographs of typical secondary drainage system for Hunting Bayou.

TABLE 3. HUNTING BAYOU WATERSHED CHARACTERISTICS

Total Drainage Area	1,976 acres (3.08 mi^2)	
Residential - (Mostly single family low income)	948 acres	48%
Commercial -	629 acres	32%
Industrial - (Meat packing plants, contractor's yards, scrap yards, chemical and building firms)	276 acres	14%
Undeveloped or under Construction - (Construction includes 610 Loop Interchange)	123 acres	6%
Impervious Cover	21%	
*Population Density	7,915 persons/$mile^2$	
Family Mean Income	$6,070.00	
Family Median Income	$5,549.00	
Median School Years Completed	9.4 years	
Home Values - Mean	$8,700.00	
Persons/Household	3.46 persons	
Rooms/Housing Unit	4.3 Rooms	

* Data Derived from 1970 Census: Census tracts 205, 206, 207 are averaged.

1 ac = .405 ha
1 mi^2 = 2.56 km^2

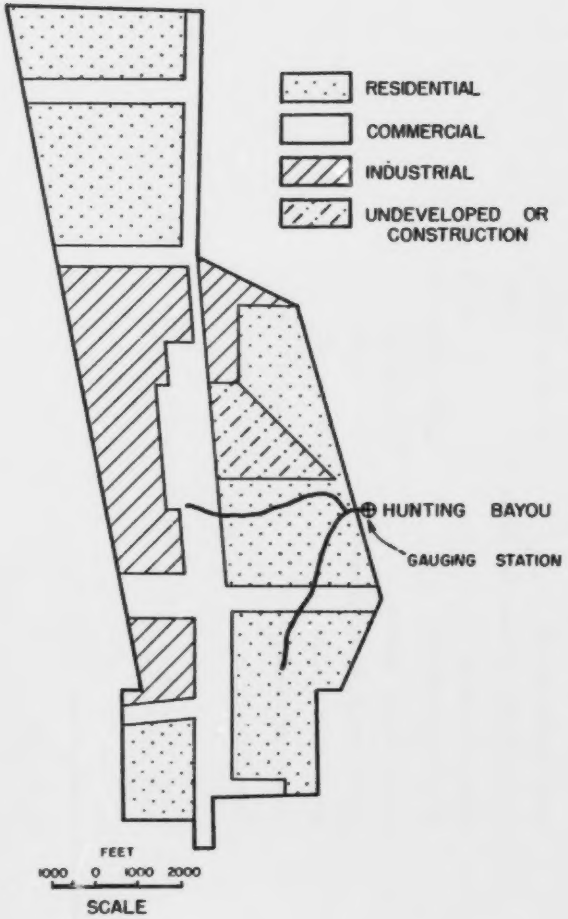
RESIDENTIAL
COMMERCIAL
INDUSTRIAL
UNDEVELOPED OR CONSTRUCTION
HUNTING BAYOU
GAUGING STATION
FEET
1000 0 1000 2000
SCALE

Figure 10. Hunting Bayou watershed land use.
1 ft = .305 m

TABLE 4. WESTBURY SQUARE WATERSHED CHARACTERISTICS

Total Drainage Area	210 acres (518ha)
Single Family Residential Areas	100%
Impervious Cover	35.4%
*Population Density	7,040 persons/mile^2
Family Median Income	$19,000/year
Median School Years Completed	14.7 years
Home Values - Mean	$29,000.00
Persons/Household	3.8 persons
Rooms/Housing Unit	7.5 Rooms

* Data derived from 1970 Census: Census tracts 427 and 428 are averaged.

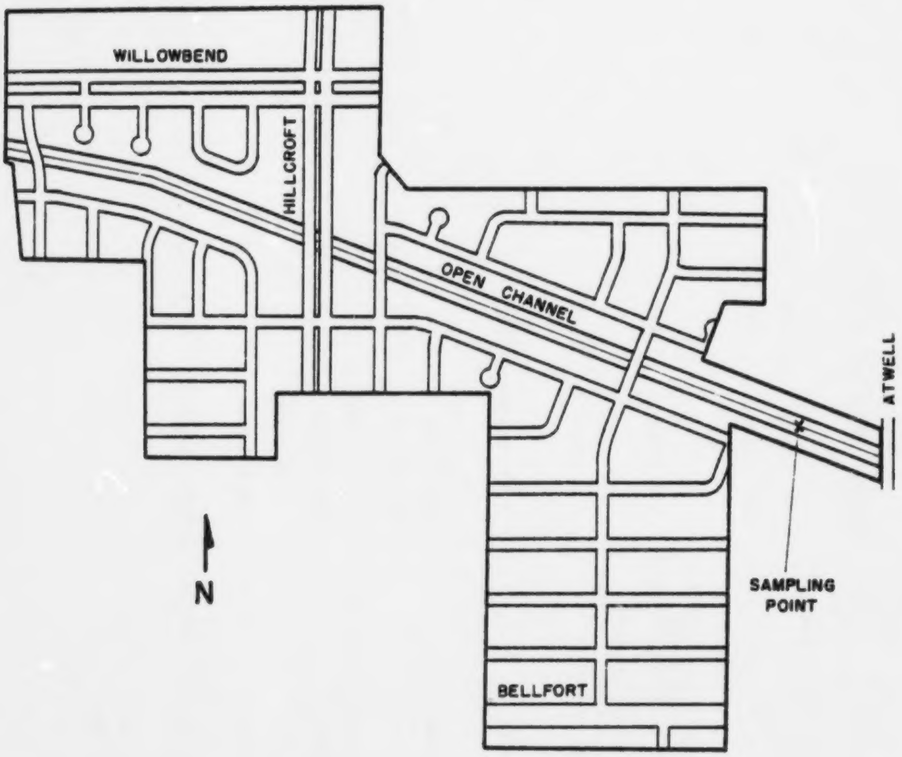
WILLOWBEND
HILLCROFT
OPEN CHANNEL
ATWELL
N
SAMPLING POINT
BELLFORT

Figure 11. Westbury Square watershed (scale 1 in = 1000 ft).
1 ac = .405 ha
1 mi = 1.6 km

Soils in the area are predominately dark clays and loams, characterized by low permeability and high available water capacity. The soils tend to be mildly alkaline or neutral. Rainfall in the area averages 39.5 in/yr (1.3/yr).

Table 5 is a comparison of characteristics from the six major watersheds monitored.

TABLE 5. WATERSHED CHARACTERISTICS

Watershed and Sampling Site:	Woodlands P-30	Woodlands P-10	Woodlands Lake A	Woodlands Lake B	Hunting Bayou	Westbury
Drainage Area, acres	21,606	16,050	483	337	1976	210
Impervious Area	1%	<1%	13%	7.1%	21%	35.4
Area Storm Sewered	0	0	0	0	28%	100%
Land Slope	.16%	.20%	.3%	.3%	.1%	.08%
Land Use Classification	Natural forest land = 90%. Development and construction = 10%.	Natural Forest land = 99%. Developed land = 1%	Variable - Construction, Residential, Commercial & Recreational.	Variable - Construction, Residential % Recreational.	Residen. = 48% Commerc. = 32% Industr. = 14% Undevel. = 6%	Residential = 100%
Demographic Notes	Wildlife	Wildlife	Planned development: upper middle class residences & recreation.	Planned development: upper middle class residences.	Lower Income Population density= 12/acre.	Middle Class Density= 11 persons/acre

1 ac = .405 ha

SECTION 5

SAMPLING AND MONITORING PROGRAMS

This chapter summarizes the field sampling and monitoring programs initiated in September 1973 and concluded in April 1976. The programs were designed to meet the following specific objectives:

1. Establish a sampling program for Bear Branch, Panther Branch and Spring Creek to determine the effects of urbanization on receiving waters.

2. Define the temporal characteristics of stormwater runoff quality and changes due to urbanization.

The sampling programs were divided into two distinct segments. First, surface waters within The Woodlands were sampled during periods of no overland runoff (dry weather flow conditions) for the occurrence and concentration of selected physical and chemical constituents. These measurements comprised a low-flow data bank to determine (a) the effect of urbanization on the water resources of The Woodlands, and (b) the water quality criteria of the lakes within The Woodlands to insure their use for recreational and aesthetic purposes. Sampling points were located for comparison of undeveloped and developing areas within The Woodlands. Sampling sites downstream provided data for establishing the impact of The Woodlands development upon water quality of the receiving body (Spring Creek).

The second phase of the sampling program concerned itself with quantifying quality of overland runoff and its subsequent impact on water resources of The Woodlands. Sampling sites were located within the Woodlands and at two developed watersheds, Hunting Bayou and Westbury Square. The storm sampling program involved development of pollutographs for at least 25 different water quality parameters per storm event. Not every storm event was evaluated but, rather, selected storms were monitored such that various seasonal and hydrologic conditions were defined.

A hydrologic network was established within the study areas, centered around continuous discharge recording stations operated and maintained by the Water Resources Division, U. S. Geological Survey (USGS), Houston, Texas, at the request of The Woodlands Development Corporation. The purpose of this network was to accurately delineate movement of water, especially surface flows. For this purpose, a weather station, rain gauges, streamflow stations and groundwater observation wells were established.

DRY WEATHER FLOW SAMPLING

The dry weather sampling program resulted in a data bank of chemical, hydrological, and physical characteristics of surface water resources at The Woodlands. All sampling sites are located in or near the Panther Branch watershed. As shown in Figure 12, these sites were located throughout the watershed from headwaters to receiving waters. Dry weather flow samples were collected only within The Woodlands watershed.

Sampling frequency at a particular site was determined by its importance in relation to monitoring effects of development. For example, Lake Harrison was sampled frequently to aid in the lake management study, while sites in Panther Branch headwaters were seldom sampled.

Quality determinations were conducted on water samples and included: temperature, dissolved oxygen (DO), pH, turbidity, total suspended solids (TSS), soluble chemical oxygen demand (COD), total COD, soluble organic carbon (SOC), total Kjeldahl nitrogen (TKN), total phosphorous (TP), orthophosphate (ortho P), ammonia (NH_2), nitrite (NO_2), nitrate (NO_3), biochemical oxygen demand (BOD), and specific conductance. Flow measurements were made where feasible, in addition to four time-of-travel measurements, covering the entire reach of Panther Branch.

STORM EVENT PROGRAM

The stormwater monitoring program used a hydrologic network combined with intensive sampling to characterize runoff quality. Runoff samples were collected at 6 sites, four located within The Woodlands, a fifth in Hunting Bayou, and a sixth at Westbury.

The Woodlands

The Woodlands sampling locations and their designations are listed below:

1.	Panther Branch at the Confluence with Bear Branch	P-10
2.	Panther Branch at Sawdust Road	P-30
3.	Outflow of Lake Harrison	Lake A
4.	Inflow of Lake Harrison	Lake B

A USGS gauging station measures streamflow at each of these sites.

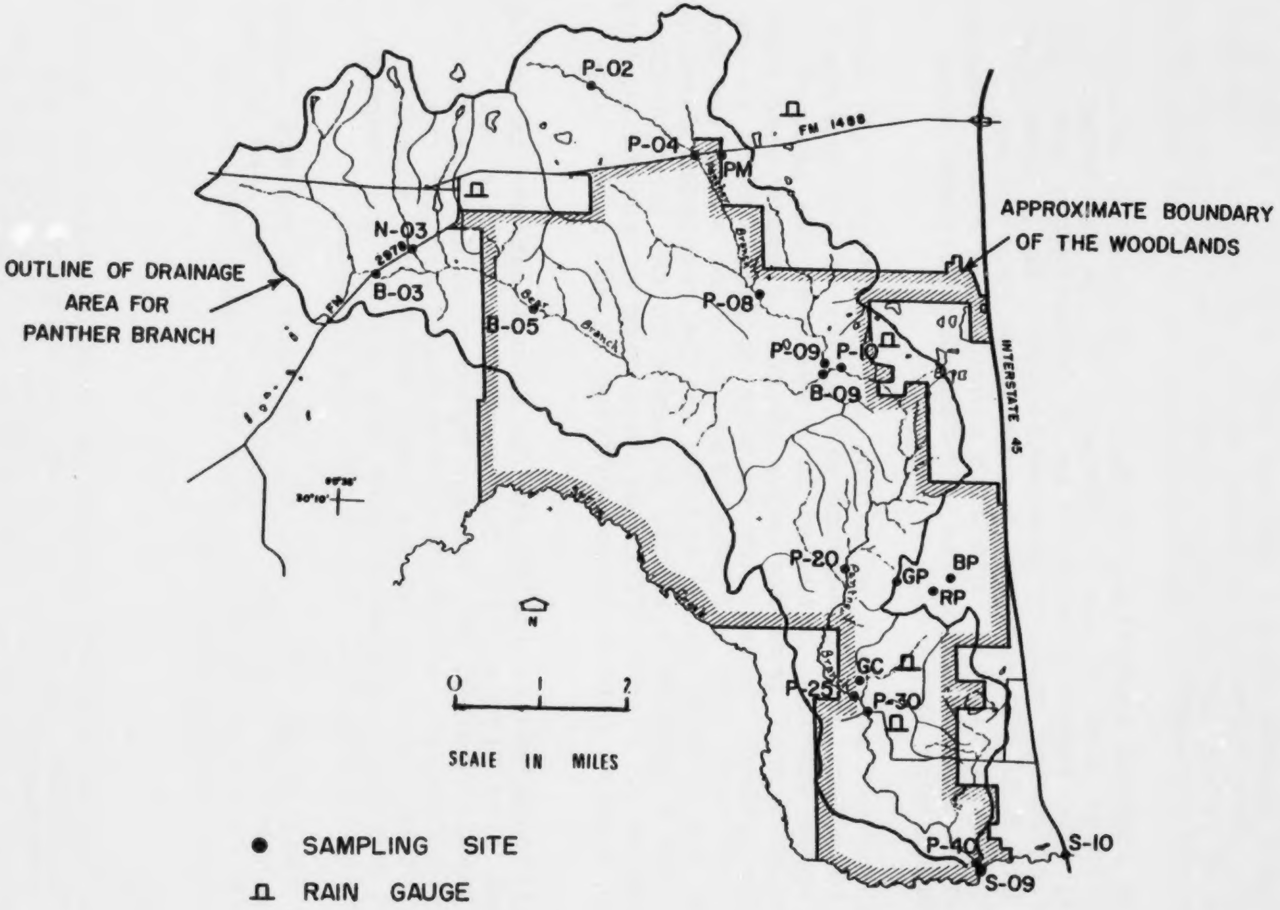
APPROXIMATE BOUNDARY OF THE WOODLANDS
OUTLINE OF DRAINAGE AREA FOR PANTHER BRANCH
INTERSTATE 45
FM 1488
FM 2978
P-02
P-04
PM
P-08
P-09
P-10
B-09
N-03
B-03
B-05
P-20
GP
BP
RP
GC
P-25
P-30
P-40
S-09
S-10
N
0
1
2
SCALE IN MILES
● SAMPLING SITE
⎍ RAIN GAUGE

Figure 12. Location of sampling sites and rain gauges within the Panther Branch watershed.

1 mi = 1.6 km

Station P-10 is located on Panther Branch 200 yards (182.9 m) downstream of the confluence with Bear Branch (see Figure 12). The watershed at this point measures 16,050 acres (6,495 ha) of predominately undeveloped pine-oak forest. Data collected from P-10 represents runoff from a natural area devoid of urban influences and, when compared to other sites, serves to determine the effects of urban influences on runoff quality. U.S.G.S. established the streamflow gauging station at P-10 in July 1974.

P-30 is located downstream on Panther Branch and includes the P-10 drainage area in its 21,606 acre (8,744 ha) watershed (Figure 12). The sampling site is in an advantageous position for monitoring runoff quality from development areas immediately upstream. U.S.G.S. has operated a streamflow gauging and monthly sampling station at this site since April 1972. Because construction at The Woodlands was a continuing process, water quality changes were expected.

Two stormwater sampling stations, shown in Figure 13, were located at Lake Harrison to measure stormwater inflow and outflow. The upper station, situated in a swale at the head of Lake B, sampled runoff from the major source of stormwater flow into the lake system. During dry weather no flow occurs in the swale. The 337 acre (136 ha) watershed was under extensive construction at the time of study and had little completed development. The Lake A gauging station, adjacent to the lake outflow box, was sampled to assess effect of detention of runoff quality. The drainage area at Lake Harrison outflow is 483 acres (196 ha).

Rainfall data was available at the five locations in or near The Woodlands (see Figure 12). The precipitation data collected at these sites determined the average hyetograph for the Panther Branch watershed during each storm event which defined the intensity, duration, time period and total amount of rainfall. The rainfall network provided data on the spatial and temporal characteristics of rainfall within the study basin.

Runoff samples were analyzed for the same parameters listed in the dry weather flow program. Chemical data was used in conjunction with flow data to derive mass flow relationships for each constituent during each storm.

Hunting Bayou

The stormwater sampling program at Hunting Bayou was similar to The Woodlands, except that only one sampling site was monitored. Stormwater samples were collected from the U.S.G.S. Hunting Bayou at Falls Street gauging station (see Figure 10). Precipitation data was available from two recorders located south of the drainage basin.

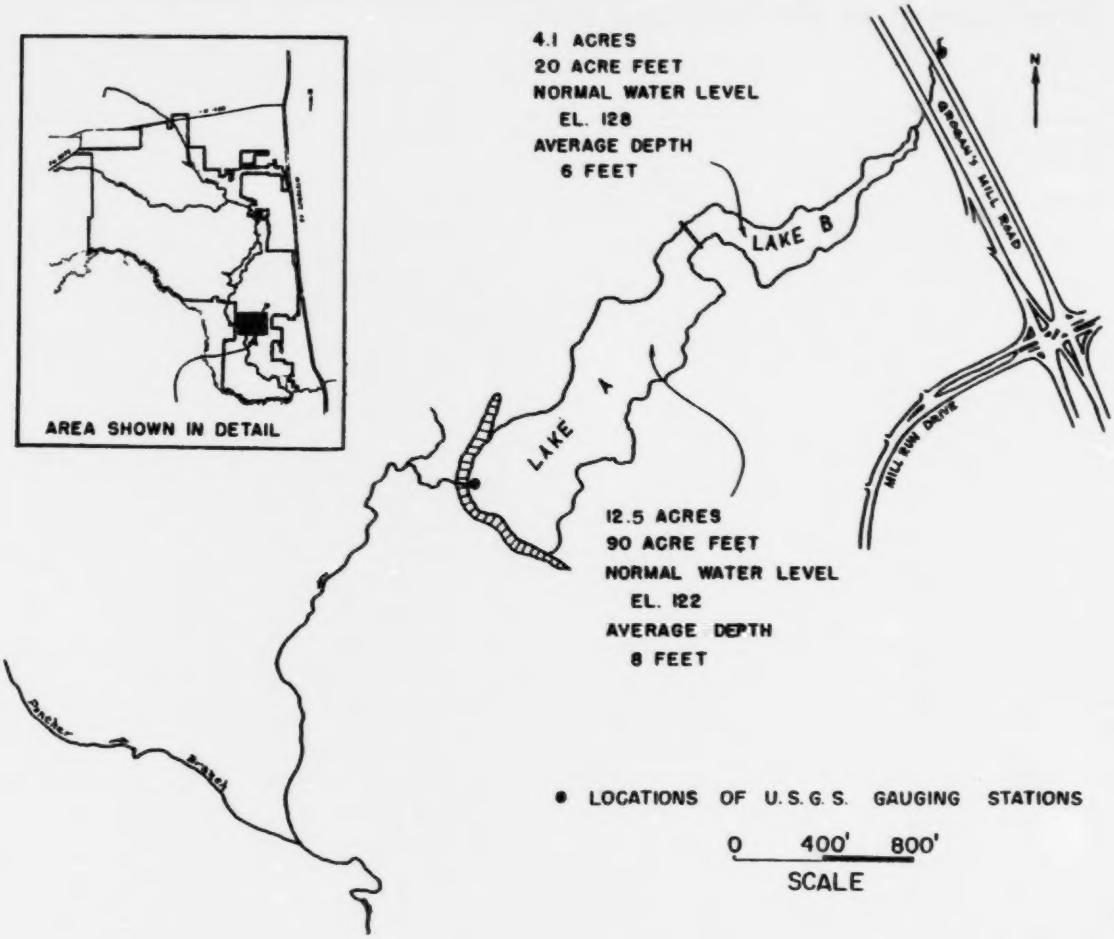
4.1 ACRES
20 ACRE FEET
NORMAL WATER LEVEL
EL. 128
AVERAGE DEPTH
6 FEET
N
GROGAN'S MILL ROAD
LAKE B
LAKE A
MILL RUN DRIVE
AREA SHOWN IN DETAIL
12.5 ACRES
90 ACRE FEET
NORMAL WATER LEVEL
EL. 122
AVERAGE DEPTH
8 FEET
Panther Branch
● LOCATIONS OF U.S.G.S. GAUGING STATIONS
0 400' 800'
SCALE

Figure 13. The Woodlands man-made lake system with locations of stormwater monitoring sites.

1 ft = .305 m

1 ac = .405 ha

Westbury

Runoff from this watershed was sampled above the Atwell St. bridge crossing the primary drainage channel (see Figure 11). Flow measurements were determined using a flow meter and precipitation measurements were made using a portable volumetric gage located at the sampling site.

SECTION 6

EXPERIMENTAL METHODS AND PROCEDURES

The sampling and analytical program is described in detail in this section to enable the reader to evaluate data reliability. The project team developed practical, effective methods for sampling stormwater runoff simultaneously at multiple sites. The methods described will be valuable to anyone planning such a program. Finally, commercial equipment utilized represents a small, but representative, sample of available instrumentation and their inherent problems.

MAJOR SAMPLING STATIONS

The location of the major sampling stations has been discussed in Section 5. Each station was equipped to varying degrees for sampling and monitoring as indicated in Table 6. P-30 and Lake A had a 110v AC power source which simplified the operation of samplers and monitors. The manometric water level sensors and recorders were maintained by the U.S.G.S. through a grant from The Woodlands Development Corporation. All flow data was compiled by the U.S.G.S. and transmitted to Rice University for integration with other stormwater data.

SAMPLING

Equipment

Samplers--

A problem inherent in all automatic samplers used, except Sigmamotor WM-1-24-R, was no provision for effective sample preservation. The U.S.G.S. samplers left the sample compartment exposed allowing access to insects and debris. The Manning S-4000 sampler provided a center compartment for filling with ice, but a test failed to cool tap water in the bottles below 59° F (15° C). Filling the compartment with dry ice would change the chemical nature of the samples (e.g., pH). Sigmamotor WM-4-24-R sampler provided space for ice also, but cooling was insufficient.

The measured flow in sample tubing from Sigmamotor WM-4-24 with 8 ft (2.44 m) head was 0.3 ft per second (.09 m/sec), less than sufficient velocity to maintain suspension of particles of 0.09 μ and specific gravity of 2.65 (16). Replacement of the pumphead

TABLE 6. FIELD EQUIPMENT OPERATED AND/OR MAINTAINED BY RICE UNIVERSITY AND USED FOR SAMPLING AND MONITORING

Site	Equipment
P-10	Discrete sampler (Sigmamotor #WM-4-24)
near P-10	Rain gage (Belfort #5-780)
P-10 and P-30	U.S.G.S. V-notch weir with manometric water level sensor (Stevens)
P-10 and P-30	Dissolved oxygen/temperature analyzer (Delta #3610) with remote stirrer (Delta #1010-10)
P-30	pH Analyzer (Delta #3412-01)
P-30	Suspended Solids (Turbidity) Analyzer (Ecologic Instrument Corp., Model 204)
P-30	U.S.G.S. discrete pumping sampler (#PS-69, Federal Interagency Sedimentation Project)
Lake B	Discrete sampler (Manning #S-4000)
Lake B and Lake A	U.S.G.S. Mailbox Gage (Float type with Stilling Well)
Lake A	Discrete Sampler (Sigmamotor #WM-1-24R)
Lake A	Weather Station (Weather Measure #M701 and #W123) including rain gage (Weather Measure #P501)
P-10, P-30, Lake B, Lake A	Float switch and latching relay for automatically starting samplers with rise in stage height
Hunting Bayou	Manual sampling, discharge from U.S.G.S. rating curve
Westbury	Manual sampling, discharge from Rice University rating curve
P-30, Lake A	110v AC which powered samplers and monitors

assembly and tygon tubing did not improve the pumping rate. For this reason, a pumphead (Masterflex #7018-20) for 0.44 in (1.1 cm) O.D. tygon tubing was adapted to replace the standard pumphead assembly. This required filing down plastic nipples on the pump housing, drilling and tapping two holes in the sampler case and fabricating an adapter sleeve between pump and motor. The resulting fill time of 3 minutes and a pumping velocity of 1.2 ft per second (.37 m/sec) with the original 1/8 in (0.3 cm) I.D. tygon sampling tubing was satisfactory for sediment suspensions at The Woodlands. A test of the sampler on Woodlands water with a 9 ft (2.7 m) head resulted in samples with turbidities within 2 FTU of grab samples (220 FTU). The Manning S-400 sample velocity was over 3 ft per second (0.92 m/sec).

Although operating characteristics of the Manning sampler were the best of the battery-operated samplers, it presented the worst breakdown record. Problems included (1) defective counter integrated circuit in the clock circuit, (2) defective capacitive probe collar, and (3) slipping stepping motor collar (sample spout). The integrated circuit was replaced, the capacitive probe was replaced with a probe of different design, and the stepping motor collar was secured with a set screw.

Float switches were fabricated which were used to activate the samplers at a predetermined rise in stream level. The float switch consisted of a reed switch activated by a magnet mounted on a disc of styrofoam, floating freely in a short length of 2 in (5.1 cm) diameter plexiglass tubing. The reed switch operated a latching relay in series with the battery and sampler. Once on, the sampler remained on even when the stream level dropped, opening the float switch. This ensured a reference back to the first sample initiating the operation.

On two separate occasions, discharged batteries connected to an 8 amp battery charger failed to recharge. This was not obvious until the sampler went dead after a few samples. Subsequently, specific gravity of the electrolyte was checked in recharged batteries. Battery problems were also encountered with the USGS sampler. Weak batteries were not able to operate pumps, however current drain under this low voltage condition blew fuses in one circuit of the sampler. A battery charger installed to operate periodically required installation of an automatic cutout switch to prevent charger overload when the sampler was operating.

Monitors--

Fouling on monitor probes and drift in calibration were the most prevalent problems encountered with the monitors. Cleaning and recalibration were necessary before each storm. Calibration of the turbidity monitor (Ecologic #204) presented unwarranted problems. Two turbidity ranges were obtainable on the monitor, but only one range had zero and calibration controls on the front panel. Internal potentiometers mounted on the printed circuit board controlled the other range independently.

Rainwater Quality Monitor--

A rainwater sampler was constructed to collect samples at a rate proportional to rainfall intensity. A tipping bucket rain gage (one/pulse/.01 in or .025 cm) was interfaced with a chromatographic fraction collector (18 x 25 ml test tubes). The rain gage also activated an event marker on the recording of accumulated rainfall. A polyethylene funnel (6 in or 15.2 cm diameter) collected rainwater and discharged it into the test tubes. A spring loaded cover protected the funnel from dust accumulation during dry weather. The first pulse from the rain gage opened the dust cover.

Sampling Procedures

Frequency--

Both temporal and spatial concentration variations are significant in stream analysis. Spatial variations are caused by floating material such as oil, sawdust, and floating biota, or by concentration gradients caused by incomplete mixing (e.g., particle distribution in laminar flow or benthic evolution of anaerobic metabolic products). Consequently, point sampling may not yield concentrations representative of average stream quality. Multi-point, cross-sectional sampling is desirable, although a single sampling point may prove adequate. Results from a cross-sectional sampling study are discussed later in this section. Single sampling points were used in this study because of the relative costs and benefits derived from multipoint sampling.

Uncertainty caused by temporal variations can be reduced by increasing sampling frequency. In stormwater runoff, temporal changes in constituents correspond approximately to changes in discharge. Sampling frequency in this study, a function of stream stage height, yielded sufficient resolution to detail pollutograph peaks. Based on project experience, empirical guidelines have been established for choosing a sampling frequency in any watershed. Starting with a selection of typical storm hyetographs and hydrographs, time to cresting, maximum discharge and total accumulated rainfall were studied. Over a three year period, sixty percent of the storm events at one test site had double peaks at 4 to 6 hours and at 20 to 26 hours. Eighty-five percent of the storms showed maximum discharge linearly correlated with total rainfall. Time to cresting appears to be primarily a function of watershed hydrology while maximum discharge can be estimated from accumulated rainfall. The average sampling frequency for a resolution of .25 ft (76 cm) rise in stream height would be given by:

$$\text{Samples/hour} = \frac{\text{estimated maximum stage height (ft)}}{\text{0.25 (ft x time to max. stage height (hr)}}$$

In this project, a minimum sampling rate of one sample per 2 hours and a maximum of one sample per 15 minutes were set for the hydrograph rise. On the falling limb of the hydrograph, a frequency half that of the rising limb gives sufficient resolution. This was reduced to one quarter the initial frequency in the last third of the sampling period. At P-10, the U.S.G.S. sampler was set to sample at one hour intervals or every quarter foot rise in stream level depending on the expected maximum discharge. Sampling frequency was halved during the falling limb of the hydrograph. Time interval sampling was used when low runoff levels were expected. Samplers at P-10 and Lake A were set to 30 minute sampling intervals for the stage rise and every hour or every other hour for the fall. Hunting Bayou, Westbury, and Lake B were sampled at 15 minute intervals on the rise and half hour to hour intervals as streamflow decreased.

Sample Processing--

Samples were in the field for a maximum period of 8 hours and were not refrigerated. Temperature within the samplers remained near ambient at all times.

Sample transportation required approximately one hour to the laboratory where each sample was processed according to the flow chart indicated in Figure 14. Non-filterable solids were determined by filtration through 0.45 μ Millipore HATF membrane filters, preserved with 40 mg of mercuric chloride mg/l of solution and refrigerated at 39° C (4° C). Preserved, filtered and unfiltered samples were stored in large screw cap culture tubes (Kimax, 195 x 25 mm). Samples for bacteriological analyses were refrigerated for at least 6-10 hours before analysis.

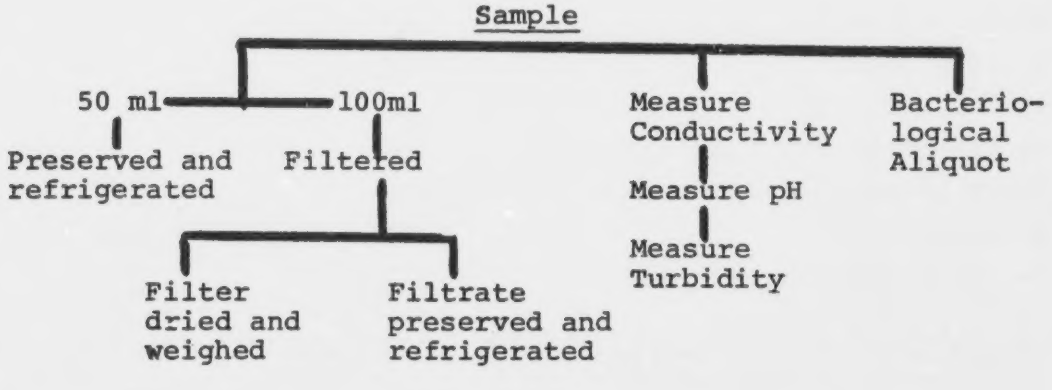
Sample
50 ml
100ml
Measure Conductivity
Bacteriological Aliquot
Preserved and refrigerated
Filtered
Measure pH
Measure Turbidity
Filter dried and weighed
Filtrate preserved and refrigerated

Figure 14. Flow chart for storm samples.

Sampling Procedures--

At Westbury and Hunting Bayou, and when only one site was sampled at The Woodlands, manual sampling was employed. A field crew consisting of 2 research assistants arrived on site before rain started. An initial grab sample was taken at onset of rain and subsequent samples taken according to the schedule outlined above. Sampling from a bridge consisted of lowering a bucket from the downstream rail. A water quality sample, and BOD bottle for Winkler DO determination, were dipped from the bucket. The cost advantages per site of automatic sampling over manual sampling by technicians can be seen in Table 7. The cost advantage is greater as storm frequency and project period increase. Uniformity is also better with automatic sampling.

For multi-site sampling at The Woodlands, manual collection was not feasible. However, if the sampler servicing crew found a sampler inoperable, one member would remain to collect samples manually while the second member reported sampler failure. Repair was then made in the field or manual sampling was continued at that site as necessary.

Sampling crews were responsible for collecting filled bottles from the automatic samplers, replacing with clean, empty bottles and resetting the samplers to initial conditions. Batteries were replaced after 3 sets of 24 bottles had been collected. Crews were instructed to record data such as time of bottle change, stage height, bottle numbers, etc.

TABLE 7. ANNUAL STORM SAMPLING COSTS IN DOLLARS PER SITE FOR TWELVE STORMS. ASSUME A TYPICAL STORM IS SAMPLED FOR 48 HOURS.

	Automated	Manual
Sampler[2]	1400	
Extra Battery[2]	30	
Battery Charger[2]	25	
Chain, Lock, Etc.[2]	50	
Equipment Maintenance (labor)[1]	250	
Other Materials (maintenance)	150	150
Sampling[1, 3]	600	2880
Overhead (60% of salaries)	510	1728
	3015	4758

[1] Assume technician at $5.00/hour [2] Capital expenditures

[3] Does not include costs and time of transportation to site

LOGISTICS OF STORMWATER SAMPLING, MONITORING AND ANALYSIS

Preparing for a Storm

Laboratory--

Completion of all analyses and data recording for the last storm event was mandatory before preparation for a new storm. Thus, inquiries could be made regarding ambiguous situations before memories lapsed, and confusion between storms was avoided. All equipment was organized and supplies restocked. Three sets of 500 ml sample bottles (24 per set) for each Rice sampler and 320 screwcap culture tubes were cleaned and boxed. Millipore HATF membrance filters were dried at 140° F (60° C), weighed and stored in numbered plastic culture dishes. Reagents for the Autoanalyzer, TKN, COD, and TP analyses, and buffers were restocked as needed. Stock standards were replaced every 4 months and tested against the new solutions as a check for continuity in accuracy. Working standards were prepared from the stock standards on the day used.

Field Equipment--

Batteries for the samplers were charged to capacity and specific gravity was tested. Dry cell batteries were replaced in all field monitors. Field checks were made of all samplers and monitors to ensure proper operation. Float switches were manually submerged to test automatic sampler functioning. The pH monitor was calibrated against pH 7 and pH 10 buffers, the DO monitors were calibrated against air saturated water, and the turbidity monitor against a Formazin standard. Float switchers were set to trip with a 1.2 in (3 cm) rise in stream level.

Storm Watch--

Three methods were employed to monitor storm activity at The Woodlands, located 40 mi (64 km) from Rice University.

Weather data, including hourly updated radar reports, were used to plot movements of frontal systems and to estimate times for arrival of storms. Telephone inquiries to The Woodlands Security Office, open 24 hours a day, gave onsite information about weather conditions. Finally, research personnel travelled to the site when rain was imminent and reported the arrival of sufficient rain for sampling. They also constituted the first sampling team shift. Westbury and Hunting Bayou were close enough (10 minutes by car) that local conditions dictated initiation of sampling.

Transportation

Although the automatic samplers could generally be left unattended for 12 to 24 hours, samples analyzed for bacterial parameters and certain chemical species undergo degradation in this period. Consequently, crews were sent every 6 hours to pick up samples. Two hours for round trip and four hours for sample collection were adequate. Shifts were started when a storm was imminent.

Manual sampling provided more difficult logistic problems. Two vehicles were necessary with overlapping shifts. Crews were assigned 8 hour shifts and left every 6 hours. This allowed for a 2 hour overlap for roundtrip travel and 6 hours for field duty. The first shift departed in the field equipment truck and the second vehicle was used as transportation to and from this truck, eliminating transfer of equipment. Transportation costs for a roundtrip from Rice University to The Woodlands was approximately $15.00 (assuming $0.15/mile or $0.09/km) if all four stations were visited.

Termination of Sampling

Sampling was terminated when discharge reached 0.1 of the maximum value or when the slope of the hydrograph was zero. This generally occurred from 24 to 72 hours after onset of the storm. Thus, it was possible that up to 12 field crews and 12 lab crews might be needed during a storm. This was accomplished by crews which were available for multiple shifts.

Laboratory Procedure

Sample Processing--

Laboratory crews, consisting of two people each, were scheduled to begin work at the estimated arrival time of the field crews. Samples were processed immediately to avoid degradation and to eliminate confusion from a backlog of samples. When the samples arrived, a staff member, always one of the lab crew, made decisions on which samples to process based on the hydrograph. Frequently, frequency of sampling was greater than necessary to adequately describe the hydrograph. An aliquot of each chosen sample was transferred to a sterile sample bottle for bacteriological examination. Each sample was shaken thoroughly to dislodge settled sediments before any transfer or measurement. Each step was laboriously described since even rudimentary precautions, obvious to staff members, were often overlooked by assistants.

A portion of each sample was then filtered through preweighed membrane filters, the transfer and filtering apparatus being "poisoned" with a small volume of sample or filtered sample before filtering the bulk of the aliquot. Mercuric chloride (2 g/100 ml demineralized water) was added, one drop per 25 ml sample, to give a final concentration of 40 mg/l. Preserved samples were stored in screwcap culture tubes at 39.2° F (4° C) until analysis. Conductivity, pH and turbidity were measured on the remaining sample. For algal bioassays, remaining sample volumes were composited into a series of larger sequential samples. For a typical storm, processing required approximately four hours per shift.

Analysis--

Research assistants, working regular 4 hour shifts, assisted with chemical analyses. Two parameters were determined on the Autoanalyzer each day with a maximum of 160 storm samples. Rather than monitor the Autoanalyzer continually for adjustment of baseline and gain, the parameters were set to approximate values and "blank-standard-blank" series run every ten samples. These served as references for calculating concentrations later. Changeover from one parameter module to another took approximately one hour including equilibration. Analyses for an entire storm were completed within 7 days.

Data Reduction and Recording--

Each person performing an analysis was responsible for calculating concentrations from the raw data. Values were recorded in laboratory notebooks and composite data sheets by the data compiler. Data sheets were spot-checked by the staff and placed in a folder with all primary data sources such as field sheets, "autoanalyzer" charts and total organic carbon (TOC) recorder charts. Data was then punched on IBM computer cards and a final data printout with dates, site description, times, discharge, and all parameters was obtained. Table 8 presents definitions used in analysis of hydrologic data. A large part of the hydrological data bank was supplied by the USGS.

OTHER SAMPLING

Dry Weather Flow

Data was collected during dry weather periods for background levels of water quantity and quality at The Woodlands. Sampling at eleven dry weather sites was conducted only if five days had elapsed since any significant stormwater runoff. Preservation, processing and analysis was identical to that for stormwater runoff samples. Sampling trips were conducted approximately once a month over a two year period in order to collect enough data for statistical analysis. One man-day (8 hours) was sufficient time to visit all sites, collect samples, and conduct field measurements. A second man-day (8 hours) was necessary for stream gaging with a pygmy meter to construct or check rating curves. In either case, about one-third of the time was spent in travel. Samples returned to the lab were filtered, preserved and analyzed for pH, conductivity and turbidity, involving about 2 man-hours of work. Chemical analyses were completed within a week using methods described in the following section.

TABLE 8. HYDROLOGICAL DEFINITIONS AND CALCULATIONS

Storm Event:	Discrete period of rainfall producing runoff monitored during the study.
Total Rainfall:	Calculated via Thiessen method using total precipitation data recorded over 2 separate drainage areas, P-10 and P-30. The Thiessen coefficients are calculated using these rain gauges: Porous Pavement, Egypt, Confluence and W. G. Jones.

P-30 Drainage Area(ac)		P-10 Drainage Area (ac)	
Porous P.	.125	Confluence	.258
Confluence	.328	Jones	.100
Jones	.075	Egypt	.642
Egypt	.472		

Duration of Rainfall:	Shortest time period during which 85% of total precipitation occurred.
Rainfall Intensity:	Total rainfall divided by duration.
Type of Storm Event:	Described type of rainfall - e.g. one period of rainfall, 2 periods of rainfall, etc.
Antecedent Rainfall Condition:	Total precipitation in 1 week period prior to storm event. Calculate same way as Total Rainfall (see above).
Total Discharge or Flow:	Volume of storm event hydrograph.
Runoff:	Overland flow volume. Equal to total discharge minus base flow.
Peak Flow:	Maximum stream discharge.
Base Flow or Groundwater Flow:	Calculated by multiplying the instantaneous discharge prior to the storm event by the time of passage.
Time of Passage:	Time from first rise in stream to 0.1 of the peak flow. If the hydrograph does not return to this level due to successive rainfall a hydrograph separation technique is used to extend the recession limb to 0.1 of the peak. When runoff is minimal and base flow greater than 0.1 of peak flow, then the inflection point on the hydrograph tail is assumed the end of passage.
Time of Concentration:	Time from first rise in stream to peak flow.

1 ac = .405 ha

Groundwater

Water samples were collected from seventeen wells at nine sites in The Woodlands. The wells consisted of PVC tubing approximately two inches in diameter driven into the soil at depths of two to five feet. Measurements were made of water level and well depth. Samples were tested in the laboratory for pH and conductivity, preserved with mercuric chloride (40 mg/l), filtered and refrigerated at 39.2° F (4° C). All analyses were performed as described below.

ANALYTICAL METHODS

Analytical Techniques

Parameters measured are listed in Table 9. All methods were approved by EPA or from EPA "Methods for Chemical Analysis of Water and Wastes" (17).

Conductivity (Industrial Instruments, Inc., #RC 16 B2 Conductivity Bridge), turbidity (Hach, #1860A), and pH (Chemtrix, #40) were measured concurrently with filtration. Soluble NH_3, NO_3, NO_2, PO_4 and COD were measured in filtered samples using a Technicon "Autoanalyzer II" system. Total COD, SOC, TKN and TP were measured using EPA methods (17). NH_3 resulting from the Kjeldahl digestion and O-PO_4 resulting from the TP digestion were measured by the "Autoanalyzer II." All analyses were completed within one week following a typical storm.

Problems

The EPA Methods (17) recommend filtration of samples through glass fiber filters to determine non-filterable solids. Filtration of Woodlands samples through Gelman type A filters left a turbid filtrate, attesting to the fine particulate and/or colloidal nature of the samples. Gelman type E and Whatman type GFC left similar turbidity in the filtrates. Various membrane filters with 0.45 μ pore size were tried, and all gave satisfactorily clear filtrates. However, various degrees of leaching were noted at levels which would interfere with analyses (Table 10). Lack of adhesion of residue to Nucleopore filters made weighing difficult. Consequently, the choice was made to use Millipore HATF filters.

Automated methods (Technicon) for TP, TKN and COD proved unsatisfactory in many respects. When samples with high TSS from stormwater runoff were analyzed on the Technicon Autoanalyzer II with continuous digestor for TP and TKN at the 0-4 mg/l level, results were inconsistent. Solids coated

TABLE 9. WATER QUALITY PARAMETERS FOR STORMWATER RUNOFF AND LOW FLOW

Always Measured

Turbidity
Conductivity
pH
Non-filterable solids
Soluble organic carbon (SOC)
Total chemical oxygen demand (COD)
Soluble COD
Total Kjeldahl nitrogen (TKN)
Total phosphorous (TP)
Ammonia (NH_3)
Nitrate (NO_3)
Nitrite (NO_2)
ortho-phosphate (ortho-P)

Sometimes Measured

Biochemical Oxygen Demand (BOD)
Volatile non-filterable solids
Total solids
Temperature
Dissolved oxygen

TABLE 10. LEACHING IN MEMBRANE FILTERS

Filter	Vol Deionized Water Filtered (ml)	Wt Loss (mg)
Millipore HAWP	50	0.5
Millipore HATF	200	0.0
Millipore EHWP	50	1.0
Nucleopore	100	0.0
Gelman Glass Fiber	50	0.4

the inside of the digestor helix reducing resolution and increasing holdup. The COD test could only be effectively run on filtered samples. Particulate matter caused negative interference with this sensitive colorimetric method. A second problem was the inability to match response with the manual COD method on semi-refractory compounds. COD's of 30-90% of the manual method were measured by the automated method. Even an increase in digestor temperature from 293° F (145° C) to 329° F (165° C) did not improve correlation significantly. The problem stems from the short digestion period (22 minutes) for the automated method compared to the 2 hour reflux period for the standard manual method. Nonetheless, this method was useful in measuring relative changes in COD.

SOURCES OF ERROR

Confidence in the data was strengthened by a series of tests leading to estimates of precision and accuracy. Experimental procedures were evaluated for sources of error and four stages were judged most critical. These were sampling, preservation, processing, and analysis. Results of these tests for four parameters are summarized in Table 11, and a discussion follows.

Analytical

Standards, with concentrations representative of natural water samples, were analyzed in replicates of five for NO_3, NH_2, phosphate and COD. Results are reported in Table 11. Analytical methods resulted in almost insignificant errors.

Preservation

Preservation methods were evaluated on high-flow samples from Panther Branch. One set of samples was filtered in the field, preserved with mercuric chloride and iced down for transport to the laboratory. A second set of samples was transported to the laboratory with no special treatment, representing normal stormwater sample handling. The samples were filtered, preserved with mercuric chloride and refrigerated along with the other samples. The following day both sets of samples were analyzed for PO_4, COD, NH_3, and NO_3^-. A week later the same preserved samples were analyzed again (see Table 11). PO_4 levels were lower than normal. Consequently, the data is not helpful in evaluating preservation techniques but indicates a problem in preservation of low level PO_4 samples. COD, NO_3 and NH_2 data confirmed adequate preservation techniques.

Sampling

Five samples were simultaneously withdrawn from a 9 square inch (58.1 cm^2) cross-section in Panther Branch using a multiport peristaltic pump sampler. The five samples were returned to the

TABLE 11. PRECISION, ACCURACY, AND PRESERVATION

	NO_3	NH_3	COD	o-PO_4
Analytical (Single Sample)	1.2%(0.4)[1]	0.6%(0.8)	1.2%(50.)	1.0%(0.1)
Cross-Sectional (12 Sample Grid 3x4)	10%(.05)	11%(.23)	20%(59.)	44%(.25)
Overall (Single Sample)	9%(.06)	12%(.22)	1%(54.)	10%(.21)
Field Filtered and Preserved, Iced and Run Immediately	.053[2]	.140	30.1	0.004[3]
Lab Filtered and Preserved and Run Immediately	.044	.155	31.6	0.000[3]
Lab Filtered and Preserved and Run One Week Later	.049	.150	30.6	0.012[3]

[1] Percent refers to $\sigma/\mu \times 100$. Number in parenthesis is μ. μ refers to the mean and σ refers to the standard deviation

[2] Single numbers refer to concentrations in mg/l.

[3] Levels of o-PO_4 were lower than normal.

laboratory, and filtered and preserved by normal procedures. Streamflows were characteristic of low-flow conditions. Samples were refrigerated and analyzed within the week. Results are reported in Table 11 as relative standard deviations (%) and concentrations analyzed. There are significant differences due to sampling.

Cross-sectional Uniformity

To determine variations in parameters due to incomplete mixing in Panther Branch, the multiport peristaltic pump sampler was set up to take either vertical or horizontal samples over a cross-section of the stream. Samples were returned to the laboratory, filtered and preserved by normal procedures. Results are reported in Table 11 as relative standard deviation (%) and concentrations analyzed. A cross-sectional sampling resulted in relatively little variation for NO_3 and NH_3 compared to the single sample variability. However, this was not the case for COD and ortho P where cross-sectional sampling led to significantly greater relative standard deviations.

SECTION 7

RESULTS AND DISCUSSION

DATA SUMMARY

Dry Weather Monitoring

Surface water quality within The Woodlands was determined during dry weather periods to establish a baseline water quality. The baseline will be useful for determining (a) the effect of urbanization on the water resources of The Woodlands over the next 20 years, and (b) immediate comparisons between stormwater runoff quality and baseflow water quality. Dry weather sampling sites are indicated in Figure 12. Dry weather, or low flow, refers to time periods when the stream stage is essentially constant. The time period following a storm event required to establish low-flow conditions depends on factors such as antecedent moisture conditions, time since last storm, rainfall duration and intensity, and groundwater elevation. In the Panther Branch watershed, low-flow conditions were normally established 4-8 days after a storm event.

Low-flow water quality data for Panther Branch, Bear Branch and Spring Creek are presented in Table 12. The headwaters in the stream system are deficient in inorganic nutrients but significant contributions in developing areas increase concentrations below P-10. The primary nutrient input is from the golf course immediately upstream of P-30. Organic concentrations are high (50 mg/l), consisting of relatively non-biodegradable (BOD $<$ 2 mg/l) leachate from decaying vegetation in the forest. COD dilution occurred downstream and the lowest concentrations were observed in Spring Creek. TSS changed drastically as the stream passed through developing areas where construction activity and borrow pits were located in the floodplain. Low-flow TSS as high as 1600 mg/l were observed at P-30.

Storm Events

Data characterizing hydrological, physical, and chemical aspects of 43 distinct runoff events resulted from 17 selected rainfall periods with streamflow being sampled simultaneously at one to four of the monitoring stations established by Rice University (refer to Site Description, Section 4). The number of

TABLE 12. SUMMARY OF LOW-FLOW WATER QUALITY PARAMETERS, AVERAGE CONCENTRATIONS

	Bear & Panther Branch above P-10	P-10 Sampling Site	Panther Br. between P-10 and P-30	P-30 Sampling Site	Spring Creek
TP	0.067	0.064	0.10	0.135	0.232
$PO-PO_4$	0.025	0.029	0.053	0.049	0.12
TKN	0.85	0.932	1.0	1.166	0.71
NH_4	0.116	0.0932	0.184	0.203	0.198
NO_2	0.006	0.0054	0.006	0.0054	0.015
NO_3	0.026	0.0244	0.029	0.059	0.359
TSS	16.45	22.6	83.0	80.7	38.3
Turbidity	12.0	14.7	46.0	41.2	30.3
Specific Conductivity	30.	46.	58.	102.	147.
SOC	23.0	19.9	19.0	15.5	19.2
Total COD	54.3	50.0	52.0	51.0	26.4
Soluble COD	40.7	40.6	40.0	37.4	19.3
BOD	2.0	1.75	1.8	2.1	1.4
pH	6.4	6.28	6.6	6.39	6.7
DO	5.5	5.23	4.8	4.27	6.7
Temp.	19.0	17.9	20.0	18.6	19.2
Discharge	1.46	3.04	2.0	5.16	116.0

Note: All measurements in mg/l except: Discharge, cfs; Turbidity, JTU; Specific Conductivity, micromhos/cm; pH, pH units; Temperature, °C.
1 cfs = .0283 m^3/sec

runoff events monitored at each sampling site were as follows:

Sampling Site	Number of Runoff Events
P-30	12
P-10	8
Lake A	8
Lake B	8
Hunting Bayou	5
Westbury Square	2

Hydrological Observations--

A summary of the hydrological data is presented in Table 13. Hydrological parameters are specifically defined in Table 8 (Section 6). Note that Total Streamflow is the sum of Baseflow and Runoff. The number of storm events monitored was limited by two drought periods, each of six month duration during the project.

Rainwater Quality--

Previous investigations indicate air pollution may contribute to surface water pollution through rainfall and/or dry fallout, even to the extent of pollutants traveling via air from industrial and agricultural regions to be deposited in undeveloped areas (18, 19). Samples collected in the Houston area and at The Woodlands assessed relative contributions of rainwater quality to stream pollution. Results presented in Table 14 indicate a substantial nutrient and COD content in rainwater at both sites. A difference exists between Houston and The Woodlands rainwater in regard to NH_3 and NO_3 content for the storms sampled. The rainwater data are compared to stormwater data in Table 15. A study of air quality at The Woodlands indicated high levels of hydrocarbons, 7.6 ppm nonmethane hydrocarbons, whose source was attributable to vegetative emissions. These ambient air hydrocarbons may contribute to the soluble COD in rainwater. The study also found an absence of NO_x at The Woodlands in contrast to serious NO_x air pollution problems in the Houston urban area (20).

At The Woodlands, rainwater nutrient concentrations were greater than runoff water, while the opposite relationship prevailed in the urban watershed. Experiments were conducted to determine the capacity of soils for stormwater nutrient removal. Four samples of soil from various locations in The Woodlands (see below) were dried and weighed. The samples were extracted with demineralized water until no further NH_3 was measured in the extract, and then equilibrated with 30 ml portions of 1 mg N/l (ammonium sulfate). After centrifugation, the supernatant was analyzed for NH_3 and then discarded. This was repeated until no further adsorption was measured. Findings indicate low levels of NH_3 are definitely adsorbed by soils, with the greatest

TABLE 13. STORM EVENT HYDROLOGY SUMMARY

#	Date	Site	Rainfall, inches	Total Stream-flow,acre-ft[a]	Base Flow,CFS	Base Flow acre-ft.	Peak Flow,CFS	Runoff, acre-ft	Runoff Coefficient[b]	Antecedent Rain	
										Week	Month,in.
1	1/18/74	Woodlands P-30	2.02	2334.0	40.0	203	1260.0	2131.0	53.0	1.65	8.0
2	3/20/74	Hunting Bayou	0.15	2.507	5.0	1.6	9.6	0.857	3.3	1.53	2.06
3	3/26/74	Hunting Bayou	0.75	42.06	9.5	17.	40.0	24.8	20.0	1.25	3.03
4	4/11/74	Hunting Bayou	0.35	12.41	4.0	6.9	11.0	5.47	9.4	0.0	3.73
5	4/22/74	Woodlands P-30	0.45	5.8	0.2	0.40	9.7	5.39	.7	0.18	2.87
6	10/28/74	Woodlands P-30	3.46	937.0	1.6	8.6	382.0	928.4	15.0	0.08	1.53
7	12/05/74	Woodlands P-30	1.59	1267.0	4.5	29.	332.0	1238.0	43.0	0.24	6.79
		Woodlands P-10	1.52	833.0	2.1	11.	280.0	822.0	40.0	0.27	7.71
8	3/04/75	Woodlands P-30	0.33	3.318	1.75	1.5	4.9	1.8	0.3	0.0	1.18
		Lake A	0.26	No Discharge		-		-	-	0.0	2.39
		Lake B	0.26	0.135	0.0	0	0.38	0.135	1.8	0.0	2.39
9	3/13/75	Woodlands P-30	0.75	119.0	1.3	7.7	49.0	111.0	2.2	0	0.38
		P-10	0.69	79.09	0.64	2.1	56.0	77.0	8.3	0	0.34
		Lake A	0.81	2.38	0.0	-	2.0	2.38	7.3	0.26	0.31
		Lake B	0.81	1.77	0.0	0	12.7	1.77	7.7	0.26	0.31
10	4/08/75	Woodlands P-30	2.76	2829.0	0.48	2.9	1100.0	2826.0	56.8	0.0	2.56
		P-10	2.43	1614.0	1.0	4.0	1170.0	1610.0	49.5	0.0	2.54
		Lake A	3.97	93.39	0.0	0	114.0	93.4	58.0	0.0	2.24
		Lake B	3.97	93.2	0.0	0	123.0	93.2	84.0	0.0	2.24
11	5/08/75	Hunting Bayou	0.81	28.9	4.6	5.13	72.5	23.8	17.7	0.71	4.21
		Westbury	0.75	7.16	0.0	0	36.0	7.16	54.0		

(Continued)

1 in = 2.54 cm
1 ac = .405 ha
1 ft = .305 m
1 cfs = .028 m^3/sec

TABLE 13. (continued)

#	Date	Site	Rainfall inches	Total Stream-flow,acre-ft[a]	Base Flow,CFS	Base Flow acre-ft.	Peak Flow,CFS	Runoff, acre-ft	Runoff Coefficient[b]	Antecedent Rain	
										Week	Month,in.
12	06/30/75	Hunting Bayou	1.85	115.7	14	22.	136	94.0	31.0	5.26	9.37
		Westbury	1.28	11.23	0	0	47	11.23	50.0	1.31	11.9
13	09/05/75	Woodlands P-30	.35	9.825	0.14	0.34	10.3	9.48	1.5	.74	1.95
		Woodlands P-10	.25	0.918	0.02	.10	0.38	0.822	0.16	.84	2.23
		Lake A	1.11	No Discharge	0	0	---	0	0	.39	.78
		Lake B	1.11	1.51	0	0	8.8	1.51	4.7	.39	.78
14	10/25/75	Woodlands P-30	2.89	117.35	0	0	64	117.35	2.3	.18	.85
		Woodlands P-10	2.82	57.09	0	0	22	57.09	1.5	.18	.85
		Lake A	3.37	18.86	0	0	15	18.86	14.0	.10	.98
		Lake B	3.37	No Data	-	-	-	-	-	.10	.98
15	03/07/76	Woodlands P-30	.713	14.88	1.45	1.3	18.5	12.6	0.9	.48	1.04
		Woodlands P-10	.68	11.24	.3	0.87	7.9	10.37	1.13	.41	1.05
		Lake A	.69	No Discharge	-	0	-	6.5	0	.98	1.42
		Lake B	.69	0.884	0	0	3.8	.884	5.0	.98	1.42
16	03/08/76	Woodlands P-30	.53	99.3	8.4	40.	32.5	59.0	6.2	1.19	1.75
		Woodlands P-10	.48	58.3	5.3	29.	23	29.1	4.5	1.09	1.73
		Lake A	.71	6.78	0	0	3.4	6.78	24.0	1.68	2.07
		Lake B	.71	2.71	0	0	6.6	2.71	13.6	1.68	2.07
17	04/04/76	Woodlands P-30	.366	45.95	.18	0.39	64	45.56	6.9	.05	2.08
		Woodlands P-10	.29	.764	.11	0.23	.37	0.537	0.1	.05	1.83
		Lake A	1.17	14.54	0	0	10	14.53	31.0	.08	3.25
		Lake B	1.17	5.10	0	0	19	5.103	15.0	.08	3.25

[a] Total streamflow is calculated to include components of overland runoff and base flow.

[b] Percentage of rainfall as runoff.

Note: in. x 2.54 = cm
ac-ft x 1.233 x 10^{-3} = hm^3
cfs x 0.028 = m^3/sec

1 in = 2.54 cm
1 ac = .405 ha
1 ft = .305 m
1 cfs = .028 m^3/sec

TABLE 14. RAINWATER QUALITY ANALYSIS

	Constituent											
Site	NH_4			NO_3			ortho P			Soluble COD		
	[1]$\bar{x}$	s	n	$\bar{x}$	s	n	$\bar{x}$	s	n	$\bar{x}$	s	n
Houston[2]	0.31	0.12	85	0.52	0.56	111	.012	.014	52	14.1	13.7	69
	$p < .05$[4]			$p < .05$			N.S.			N.S.		
Woodlands[3]	0.22	0.09	19	0.31	0.17	20	.039	.056	19	15.4	7.07	20

1. $\bar{x}$ = mean values in mg/l, s = standard deviation, n = number of samples.
2. Rain samples collected at Rice University on 7/11/75, 7/23/75, 8/12/75.
3. Rain samples collected at The Woodlands on 11/19/75,2/20/76.
4. Student "t" test using Welch approximations. $p = .05$ level of significance. N. S. = not significant. (Remington and Schork, Statistics with Applications to the Biological and Health Sciences. Prentice-Hall, Inc., Englewood Cliffs, N.J., 1970.

TABLE 15. COMPARISON OF RAINWATER AND RUNOFF QUALITY IN HOUSTON AND AT THE WOODLANDS (ALL UNITS IN mg/l)

Constituent	Houston		The Woodlands	
	Rain	Runoff[1]	Rain	Runoff[2]
soluble COD	14	20	15	44
NH_3	.31	2.1	.22	.08
NO_3	.52	.38	.31	.05
ortho P	.01	.57	.04	.005

[1] Avg. of stormwater data collected at Hunting Bayou

[2] Avg. of stormwater data collected at P-10

adsorption occurring in undisturbed forest soil:

Soil Sample	Total mg N/g Adsorbed[1]
Golf Course	0.027
Roadside	0.022
Swale	0.017
Woods	0.043

[1] mg N/g dry soil adsorbed in equilibrium with 1 mg N/l solution of ammonium sulfate.

The data suggest that NH_3 in rainwater is adsorbed to a large extent in undisturbed forest soils where it is metabolized by plants or nitrified and possibly denitrified by soil microorganisms. In an urban area receiving the same ammonia rainwater load, there is more impervious area resulting in higher ammonia in the runoff. In addition, soils in an urban area have a lower NH_3 adsorption capacity and lower NH_3 utilization rate.

Of greatest significance is the effect of nutrient wash off on lake eutrophication at The Woodlands. Ward and King (21) have shown nitrogen to be the limiting nutrient for algal growth in The Woodlands lakes during wet weather. As development continues, increasing nitrogen input from stormwater runoff can be expected and lake enrichment may result.

Groundwater Quality--

Surface water quality at The Woodlands is influenced by infiltration from the perched water table. To determine groundwater quality, samples were collected from 17 wells located within the watershed 3 days after a 2.8 in. (7.1 cm) rainfall. The wells consist of 2 in. (5 cm) I.D. PVC pipe driven 2 to 5 ft (0.6 to 1.5 m) into the soil. Results presented in Table 16 indicate The Woodlands groundwater contains greater amounts of nutrients but less organic material than runoff. Low pH values are consistent with the naturally acid soil due to the presence of humic and tannic components, high clay and low carbonate content.

TABLE 16. COMPARISON OF GROUNDWATER QUALITY AFTER RAINFALL TO RUNOFF WATER QUALITY, THE WOODLANDS

Constituent[1]	Groundwater[2]	Runoff[3]
TKN	2.1	1.37
NH_3	1.4	0.08
Total P	0.09	0.06
o-PO_4	0.02	0.003
pH	5.1	5.9
Specific Conductance	200	110
Total COD	22	59
SOC	10	22

[1] Data in mg/l except specific conductance as micromhos/cm and pH in pH units.

[2] Mean concentrations of samples collected within 3 days of 2.8 in (7.1 cm) rainfall on April 14, 1975.

[3] Mean concentrations for runoff samples collected at P-10 during April 8, 1975 storm event.

Stormwater Runoff Quality--

Discrete water samples were collected for the purpose of defining temporal stormwater quality during a storm. Over 850 stormwater samples were collected and over 12,000 separate water quality analyses were performed. A summary of the water quality data is presented in Table 17, including mass load and flow weighted mean concentrations for each parameter. Mean concentrations are calculated from discrete sample results weighted according to instantaneous stream discharge at the time of collection. Mass load represents total amount of constituent passing the monitoring site during the runoff event. Mass load is incalculable where no discharge occurred, as with lake storage of stormwater.

All water quality samples collected are representative of the total streamflow volume (including baseflow) which is reported in Table 17. In the majority of events, overland runoff is approximately equal to total streamflow and samples can be considered representative of runoff. For storm events producing low runoff, water quality is influenced by baseflow.

Comparison of Stormwater Runoff and Wastewater Quality

A water quality comparison of stormwater runoff to untreated and treated municipal wastewater is presented in Table 18. Stormwater runoff quality is better than untreated wastewater except for excessive solids concentrations. Treatment of wastewater reduces the oxygen demand below levels of stormwater runoff but sophisticated removal processes are required to reduce nutrient levels in wastewater below those in stormwater runoff.

OBSERVED TEMPORAL AND SPATIAL VARIATIONS IN STORMWATER RUNOFF QUALITY

Pollutograph Analysis

A pollutograph is defined as a plot of pollutant concentration versus time during a storm event. Temporal changes of water quality during runoff events are important to the understanding of the impact of these non-point sources on stream quality. The time-concentration relationship is also critical in consideration of stormwater treatment alternatives. Pollutographs observed during the study exhibited the five generalized patterns shown in Figure 15. These concentration patterns were common to all watersheds, although levels of a particular parameter were site dependent.

Specific conductance of groundwater which feeds streamflow is high due to dissolved minerals and as a result stormwater inflow decreases stream conductance similar to the second pollutograph shown in Figure 15. This dilution pattern applies to other streamwater constituents, including some found in wastewater effluents, which are concentrated in dry-weather flow. The concentrations of SOC, soluble COD and total COD often increased as runoff progressed, with highest concentrations observed at the end of the runoff. Streamflow contributions from interstitial and bank storage flow is greatest late in runoff and could account for the pattern if enriched by contact with soils serving as an organic carbon source. DO concentrations in stormwater increased proportionally to flow and assumed a hydrograph-shaped

TABLE 17. RUNOFF WATER QUALITY SUMMARY-- MASS FLOW AND WEIGHTED AVERAGE

Storm #	Date	Site	Streamflow acre-feet	$o\text{-}PO_4$ lbs	$o\text{-}PO_4$ $\bar{x}$ conc mg/l	TP lbs	TP $\bar{x}$ conc mg/l	NH_3 lbs	NH_3 $\bar{x}$ conc mg/l
1	01/18/74	The Woodlands P-30	2334	7.73	.001	No Data		215.	.034
2	03/20/74	Hunting Bayou	2.51	2.96	.437	No Data		16.5	2.44
3	03/26/74	Hunting Bayou	42.1	45.1	.395	46.4	.407	287.	2.51
4	04/11/74	Hunting Bayou	12.4	16.9	.503	30.3	.899	24.6	.732
5	04/22/74	The Woodlands P-30	5.80	0.70	.044	7.53	.478	5.27	.334
6	10/28/74	The Woodlands P-30	937.	43.0	.017	256.	.101	236.	.093
7	12/05/74	The Woodlands P-30	1267	33.7	.010	328.	.096	355.	.103
		The Woodlands P-10	833.	14.1	.006	171.	.076	199.	.088
8	03/04/75	The Woodlands P-30	3.32	0.23	.025	1.14	.127	.880	.100
		Lake A	Stored	NA	.008	NA	.097	NA	.062
		Lake B	.135	.012	.033	.077	.210	.238	.650
9	03/13/75	The Woodlands P-30	119.	3.15	.010	52.3	.162	22.2	.069
		The Woodlands P-10	79.1	1.15	.005	19.7	.092	19.2	.089
		Lake A	2.38	.043	.006	.893	.137	.760	.117
		Lake B	1.77	.102	.021	2.54	.530	1.06	.221
10	04/08/75	The Woodlands P-30	2829	85.2	.011	675.	.088	1144	.149
		The Woodlands P-10	1614	15.0	.003	264.	.060	339.	.077
		Lake A	93.4	3.75	.015	26.2	.103	39.6	.156
		Lake B	93.2	1.25	.005	27.9	.110	28.1	.110
11	05/08/75	Hunting Bayou	28.9	40.4	.516	84.2	1.08	94.4	1.20
		Westbury	7.16	13.8	.710	14.2	.730	17.3	.890

NA - Not applicable - a mass loading was not calculable.
Stored - No discharge of stormwater from the lake system.

1 ac = .405 ha
1 ft = .305 m
1 lb = .4536 kg

(continued)

TABLE 17. (continued)

NO_2		NO_3		TKN		TSS		SOC		Total COD		Soluble COD	
lbs	$\bar{x}$ conc mg/l	lbs	$\bar{x}$ conc mg/l	lbs x10	$\bar{x}$ conc mg/l	lbs x10^3	$\bar{x}$ conc mg/l	lbs x10^2	$\bar{x}$ conc mg/l	lbs x10^2	$\bar{x}$ conc mg/l	lbs x10^2	$\bar{x}$ conc mg/l
5.30	.001	181.	.029	No Data		1492	236.	No Data		No Data		No Data	
.353	.052	2.96	.438	No Data		.480	70.9	2.59	38.3	5.18	76.6	No Data	
7.42	.065	58.1	.509	40.1	3.52	22.5	197.	18.5	16.3	114.	99.8	No Data	
2.18	.065	11.4	.338	5.25	1.56	4.10	122.	18.6	55.3	34.3	102.	10.8	32.0
.170	.011	3.71	.235	2.11	1.34	14.8	939.	2.74	17.4	14.7	93.1	8.53	54.2
12.5	.005	94.2	.037	No Data		775.	305.	455.	17.9	No Data		859.	33.8
18.5	.005	79.9	.023	311.	.905	296.	86.2	No Data		1962	57.1	1405	40.9
.280	.000	27.6	.012	187.	.826	60.5	26.8	No Data		1400	62.0	988.	43.7
.055	.006	.960	.107	1.50	1.66	.426	47.0	.802	9.00	3.02	33.4	2.88	32.0
NA	.008	NA	.189	NA	.829	NA	166.	NA	14.0	NA	47.0	NA	32.5
.016	.044	.131	.357	.066	1.79	.104	283.	.027	7.35	.181	49.2	.120	32.6
1.08	.003	35.9	.111	35.1	1.09	28.8	90.0	69.8	21.6	192.	59.3	143.	44.2
.750	.003	22.1	.103	34.5	1.61	14.4	67.0	48.2	22.5	136.	63.4	111.	51.9
.065	.010	1.32	.203	.401	.620	.991	152.	.900	13.8	2.47	38.0	1.87	28.8
.113	.024	1.74	.362	1.99	4.14	13.8	2877	.705	14.7	5.90	123.	1.37	28.5
73.1	.009	1181	.154	1065	1.39	1312	171.	1563	20.4	4037	52.6	2981	38.8
17.1	.004	284.	.065	600.	1.37	168.	38.5	962.	22.0	2572	58.8	1888	43.1
8.24	.032	70.4	.280	33.3	1.31	61.9	245.	34.4	13.6	106.	41.8	66.8	26.4
2.18	.009	37.6	.150	47.1	1.86	322.	1273	40.8	16.2	161.	63.7	82.0	32.0
4.52	.058	40.1	.511	25.5	3.25	16.2	207.	13.7	17.5	140.	179.	27.5	35.1
.754	.039	7.20	.371	4.25	2.19	.474	24.4	3.13	16.1	10.4	53.8	6.09	31.4

(continued)

1 ac = .405 ha
1 ft = .305 m
1 lb = .4536 kg

TABLE 17. (continued)

				ortho P		TP		NH_3	
Storm #	Date	Site	Streamflow acre-feet	lbs	$\bar{x}$ conc mg/l	lbs	x conc mg/l	lbs	$\bar{x}$ conc mg/l
12	06/30/75	Hunting Bayou	116.	212.	.677	403.	1.28	660.	2.10
		Westbury	11.2	17.1	.560	34.6	1.14	4.40	.145
13	09/05/75	The Woodlands P-30	9.82	1.67	.063	4.75	.180	5.36	.201
		The Woodlands P-10	.918	.051	.021	.082	.033	.075	.030
		Lake A	Stored	NA	.011	NA	.050	NA	.069
		Lake B	1.51	.148	.035	.608	.148	.567	.138
14	10/25/75	The Woodlands P-30	117.	12.0	.038	46.7	.147	26.1	.082
		The Woodlands P-10	57.1	.342	.002	7.32	.047	8.34	.054
		Lake A	18.9	.068	.001	1.35	.026	2.27	.044
		Lake B	No Data	NA	.027	NA	.081	NA	.108
15	03/07/76	The Woodlands P-30	14.9	1.18	.029	No Data		2.58	.064
		The Woodlands P-10	11.2	.039	.003	No Data		1.67	.055
		Lake A	Stored	NA	.005	No Data		NA	.063
		Lake B	.884	.124	.052	No Data		.089	.037
16	03/08/76	The Woodlands P-30	99.3	7.92	.029	No Data		46.8	.174
		The Woodlands P-10	58.3	.217	.001	No Data		3.61	.023
		Lake A	6.78	.131	.007	No Data		.723	.039
		Lake B	2.71	.088	.012	No Data		.247	.034
17	04/04/76	The Woodlands P-30	45.9	5.38	.043	18.7	.149	48.9	.390
		The Woodlands P-10	2.83	.027	.003	.468	.061	1.21	.158
		Lake A	14.5	.148	.004	2.49	.063	4.79	.121
		Lake B	5.10	.077	.006	1.07	.078	1.66	.120

NA - Not applicable - a mass loading was not calculable.
Stored - No Discharge of stormwater from the lake system.

1 ac = .405 ha
1 ft = .305 m
1 lb = .4536 kg

(continued)

TABLE 17. (continued)

NO_2		NO_3		TKN		TSS		SOC		Total COD		Soluble COD	
lbs	$\bar{x}$ conc mg/l	lbs	$\bar{x}$ conc mg/l	lbs x10	$\bar{x}$ conc mg/l	lbs x10^3	$\bar{x}$ conc mg/l	lbs x10^2	$\bar{x}$ conc mg/l	lbs x10^2	$\bar{x}$ conc mg/l	lbs x10^2	$\bar{x}$ conc mg/l
14.0	.044	117.	.373	124.	3.94	51.0	182.	71.6	22.8	252.	80.4	61.2	19.5
.803	.026	11.8	.388	4.51	1.48	2.13	69.8	5.09	16.7	11.8	38.9	4.36	14.3
.480	.018	8.13	.305	1.16	.435	2.67	100.	No Data		No Data		9.40	35.2
.007	.002	.075	.030	.024	.097	.016	6.54	No Data		No Data		.852	34.5
NA	.009	NA	.009	NA	.172	NA	24.0	No Data		No Data		NA	19.5
.047	.012	.955	.233	.168	.410	6.70	1633	No Data		No Data		.878	21.4
1.56	.005	47.0	.147	9.69	.305	53.8	169.	66.0	20.7	135.	42.4	77.0	24.2
.690	.005	4.67	.030	4.04	.261	1.18	7.60	37.8	24.4	70.0	45.1	58.9	38.0
.143	.003	1.19	.023	.942	.184	1.85	36.2	2.38	4.66	10.9	21.2	7.21	14.1
NA	.010	NA	.113	NA	.280	NA	421.	NA	20.6	NA	48.9	NA	24.2
.593	.015	10.2	.252	No Data		9.55	237.	5.55	13.7	No Data		12.2	30.2
.321	.010	1.43	.047	No Data		6.47	212.	6.72	22.0	No Data		14.2	46.6
NA	.011	NA	.076	No Data		NA	184.	NA	8.00	No Data		NA	15.4
.035	.014	.393	.164	No Data		1.77	738.	.322	13.4	No Data		.631	26.3
3.70	.014	48.0	.178	No Data		78.1	290.	42.4	16.0	No Data		88.3	32.8
1.66	.011	3.69	.023	No Data		20.6	130.	41.4	26.0	No Data		86.6	54.7
.225	.012	1.64	.089	No Data		3.27	177.	1.11	6.05	No Data		2.73	14.8
.328	.045	1.31	.141	No Data		3.07	419.	.962	13.1	No Data		1.78	24.3
2.13	.017	52.9	.420	25.5	2.04	No Data		18.5	14.8	61.7	49.3	43.3	34.6
.052	.007	1.04	.135	.516	.672	No Data		1.27	16.5	3.08	40.0	2.97	38.7
.205	.005	4.53	.112	2.90	.735	No Data		3.98	10.1	7.88	20.0	9.20	23.3
.163	.012	4.92	.355	1.29	.929	No Data		1.94	13.3	6.00	43.3	5.15	37.2

(continued)

1 ac = .405 ha
1 ft = .305 m
1 lb = .4536 kg

TABLE 17. (continued)

Storm #	Date	Site	Turbidity	pH	Temp.	Spec. Cond.	D O	Total Solids	BOD
1	01/18/74	The Woodlands P-30	150	6.5	14.7	-	9	-	-
2	03/20/74	Hunting Bayou	-	-	20	-	2.5	-	17
3	03/26/74	Hunting Bayou	135	-	15	-	4.6	-	-
4	04/11/74	Hunting Bayou	100	6.5	22	545	2.25	-	22
5	04/22/74	The Woodlands P-30	305	6.5	22	200	3.5	-	-
6	10/28/74	The Woodlands P-30	250	5.7	-	110	-	450	6.1
7	12/05/74	The Woodlands P-30	65	6.0	-	58	-	385	-
		P-10	20	5.2	-	56	-	110	-
8	03/04/75	The Woodlands P-30	35	7.5	14	375	8.3	-	-
		Lake A	121	7.5	16	115	7.8	-	-
		Lake B	184	8.1	-	415	7.6	-	-
9	09/13/75	The Woodlands P-30	50	6.6	13.5	280	6.4	-	-
		P-10	30	6.1	13.3	290	7.2	-	-
		Lake A	105	7.5	17	160	7.7	-	-
		Lake B	1200	7.8	11.5	185	7.4	-	-
10	04/08/75	The Woodlands P-30	130	6.8	-	103	7.8	-	-
		P-10	28	5.9	19	110	6	-	-
		Lake A	165	7.54	20	140	7.65	-	-
		Lake B	330	6.9	20	80	7.1	-	-
11	05/08/75	Hunting Bayou	110	7.6	24	460	3.2	-	-
		Westbury Square	18	7.3	-	175	3.34	-	-
12	06/30/75	Hunting Bayou	140	7.2	27	360	3.3	-	-
		Westbury Square	14	7.3	-	125	4.6	-	-
13	09/05/75	The Woodlands P-30	100	7.05	-	208	-	-	-
		P-10	7	6.6	-	280	-	-	-
		Lake A	19	8.01	-	336	-	-	-
		Lake B	830	7.6	-	135	-	-	-
14	10/25/75	The Woodlands P-30	120	7.4	18.5	275	7.5	-	-
		P-10	12	5.8	18	247	6.6	-	-
		Lake A	24	8.1	22	536	8.2	-	-
		Lake B	325	7.4	19	167	7.6	-	-
15	03/07/76	The Woodlands P-30	74	-	-	281	-	-	-
		P-10	12	-	-	410	-	-	-
		Lake A	-	-	-	-	-	-	-
		Lake B	137	-	-	155	-	-	-
16	03/08/76	The Woodlands P-30	138	-	-	-	-	-	-
		P-10	5	-	-	365	-	-	-
		Lake A	-	-	-	410	-	-	-
		Lake B	120	-	-	115	-	-	-
17	04/04/76	The Woodlands P-30	70	7.3	-	318	-	-	-
		P-10	7	6.9	-	284	-	-	-
		Lake A	53	7.9	-	363	-	-	-
		Lake B	110	7.2	-	125	-	-	-

All measurements in mg/l except: Turbidity in JTU; pH in pH units; Temperature in Centigrade and Specific Conductance in micromhos/cm.

TABLE 18. WATER QUALITY FOR STORMWATER RUNOFF, UNTREATED SEWAGE, AND TREATED SEWAGE (ALL UNITS IN mg/l)

STORMWATER RUNOFF[1]	Total Suspended Solids	Total Kjeldahl Nitrogen	Total Phosphorous	Total Chemical Oxygen Demand
Forest (P-10)	6.5 - 67	0.10 - 1.61	0.03 - 0.09	43 - 63
Forest Under Development (P-30)	109 - 321	0.06 - 1.41	0.13 - 0.30	40 - 51
Lake B	283 - 2877	1.79 - 4.14	0.11 - 0.53	49 - 123
Lake A	24 - 245	0.17 - 1.31	0.05 - 0.14	38 - 47
Hunting Bayou	71 - 207	1.56 - 3.94	0.41 - 1.28	77 - 179
Westbury Square	24 - 70	1.48 - 2.19	0.73 - 1.14	39 - 54
SEWAGE				
Untreated[1]	200	40	10	350
Secondary Treatment	20	30	10	40
Advanced Treatment[2]	5	10	1	15

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[1] Range of flow-weighted mean concentrations for number of storm events monitored.

[2] The Woodlands Water Reclamation Plant - Design Efficiency

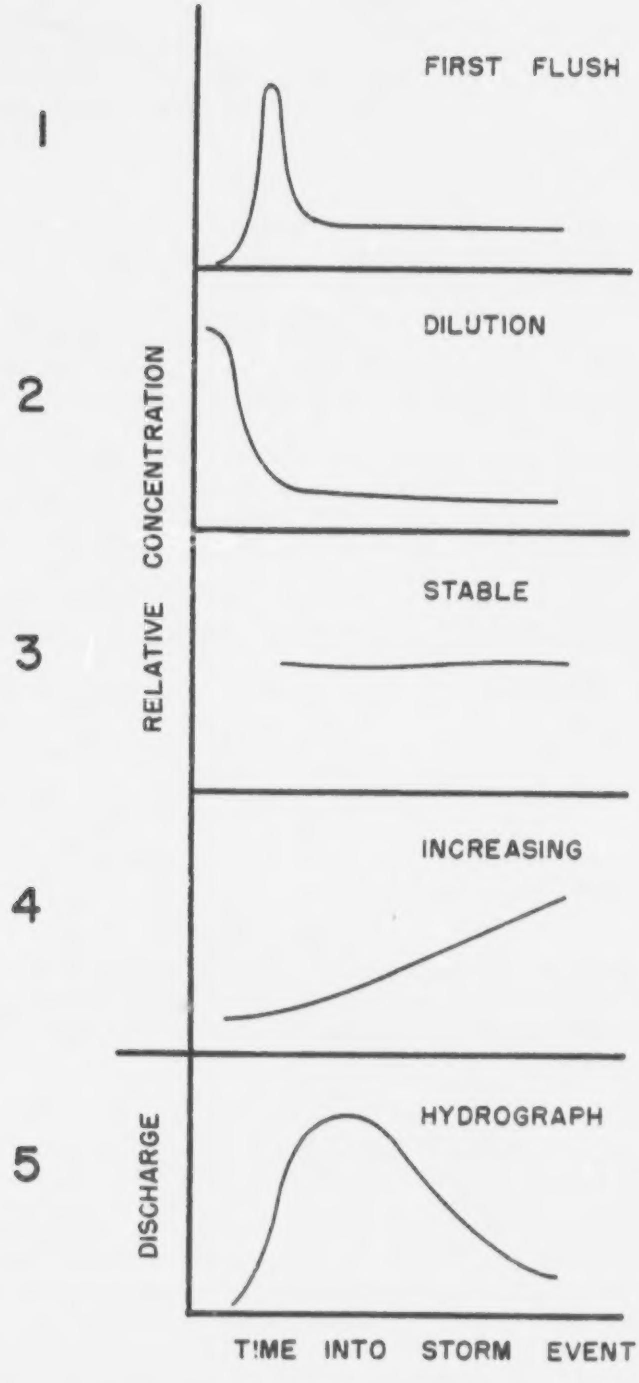


Figure 15. Generalized pollutographs observed for stormwater parameters.

pollutograph (Figure 15). Increased reaeration at greater streamflows accounts for this phenomena. Several parameters observed at site P-10 remained at a constant level throughout the hydrograph, including pH, NH_3, NO_3, NO_2 and soluble COD. This pattern was not commonly observed at the other watersheds where land use is diversified.

First Flush--

The "first flush" pollutograph pattern is characterized by an abrupt rise in concentration early in the runoff event. At Hunting Bayou, the "first flush" was observed for the greatest number of runoff constituents including TSS, turbidity, o-PO_4, TKN, TP, NH_3, NO_2 and NO_3. Turbidity and TSS parameters exhibited the highest peak values over baseline, while peak values for other constituents were less pronounced.

The "first flush" was observed at all sites as indicated by a comparison of TSS pollutographs at P-10, Westbury and Hunting Bayou presented in Figure 16. The storm events described were similar in peak discharge and runoff volume.

Site	Peak SS Concentration (mg/l)	Peak Discharge (cfs)	Peak Mass Load (kg/sec)
P-10	178	32	0.161
Westbury	250	40	0.283
Hunting Bayou	431	70	0.854

1 cfs = .028 m^3/sec
1 lb = .454 kg

The "first flush" phenomena in an urbanized setting is more pronounced due to enhanced availability of pollutants on impervious surfaces and higher runoff velocities characteristic of urban drainage systems.

Observations at P-10 suggest that "first flush" in an undeveloped watershed results from stream bed sediment transport. Table 19 compares three significantly different storm events at P-10. Peak TSS concentration, the "first flush" indicator, is apparently unrelated to the discharge characteristics of the storm event. Closer inspection suggests that peak TSS concentration increases with stream instantaneous discharge at flows up to 32 cfs (.905 m^3/sec). Panther Branch leaves its low-flow channel at 32 cfs (.905 m^3/sec) and further increases in discharge over the broad floodplain results in negligible changes in linear flow velocity. Therefore, "first flush" is greatly influenced by stream bed sediment availability in a natural watershed.

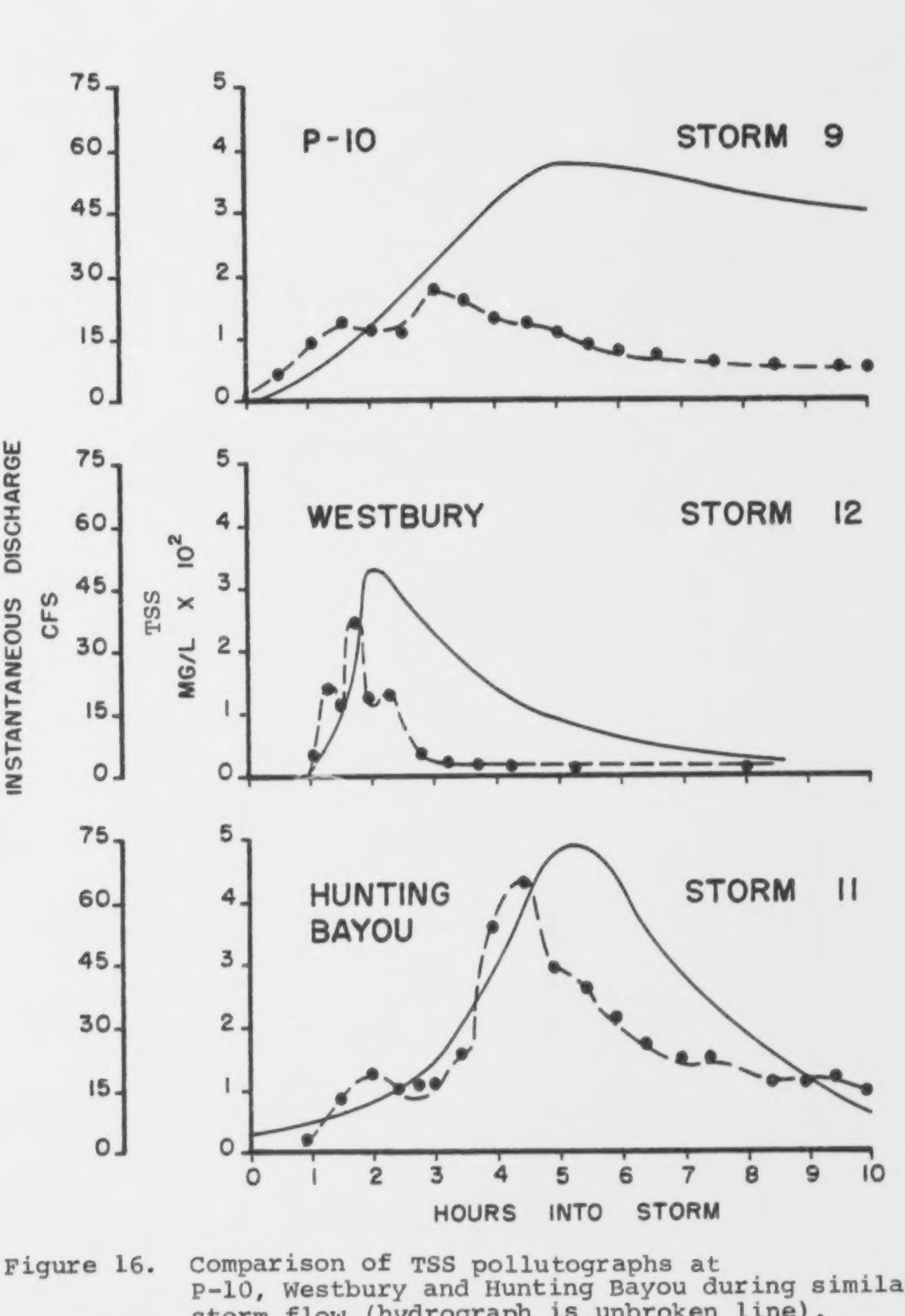


Figure 16. Comparison of TSS pollutographs at P-10, Westbury and Hunting Bayou during similar storm flow (hydrograph is unbroken line). 1 cfs = .028 m^3/sec

TABLE 19. COMPARATIVE DATA OF FIRST FLUSH EFFECT FOR THE 3 STORM EVENTS AT SITE P-10

	STORM EVENT DATE AND NUMBER		
	12/5/74	3/13/75	4/8/75
"First Flush" Effect			
Peak TSS Concentration (mg/l) (indicator of flush)	130	178	226
Stream Instantaneous Discharge at Flush (cfs)[1]	14	32	32
Time into Runoff Event of Flush (Hours)	0.75	3	2
Streamflow			
Peak Discharge Rate (cfs)	280	56	1170
Time into Runoff Event of Peak Discharge (Hours)	20.5	5.5	15.75
Elapsed Time between Peak Discharge and Flush	19.75	2.5	13.75

[1] 1 cfs = .028 m^3/sec

Effect of Land Use on Stormwater Runoff Quality

Pollutant Load-Runoff Relationships--

Total pollutant loads were plotted against total runoff of each storm event and regression lines were fitted to correspond to Hunting Bayou, Westbury, P-10 and P-30 watersheds. Fitted lines and associated correlation coefficients are shown in Figures 17-20 for the constituents TSS, total COD, TKN, TP, NO_3, NH_3, soluble COD and SOC. Correlation coefficients (r) for a majority of the parameters were greater than 0.8, however, three cases showed poor correlation; P-30, NO_3 ($r = 0.775$), Westbury, NH_3 ($r = 0.397$), and Hunting Bayou, SOC ($r = 0.161$).

NO_3, NH_3, TKN and TP relationships, shown in Figures 17-18, indicated that the urban watersheds produce nutrient loads greater than the forested watersheds. In all cases Hunting Bayou nutrient loadings are highest, followed in order by Westbury, P-30 and P-10.

TSS loads are highest at P-30 as a result of construction activities in the watershed. Urban runoff TSS loading is greater than forest runoff loading (Figure 19).

Runoff loads for nonspecific parameters (total COD, soluble COD and SOC), shown in Figures 19-20 are higher in forested watersheds than urban watersheds, with the exception of high total COD loads from Hunting Bayou. The data suggest organic material in runoff decreases with urbanization, however, insoluble pollutants, sediments and oils will increase.

A ranking of the four watersheds, on a lb/ac/in of runoff basis, illustrates the relative conditions for each site and pollutant. Table 20 shows these rankings for mean regression values at one inch of runoff for all parameters and sites. Confidence intervals (95%) are included in Table 20 to indicate significant differences in pollutant loads at 1 inch runoff. Confidence limits for Westbury show a particularly large spread due to the small number (2) of storms monitored for that watershed. Signifcant differences for the total COD, soluble COD and SOC cases are indicated, with some overlap in the TSS case. The pattern of nutrient response for the urban developing and forested watersheds is distinctive, with the urban response producing loads up to an order of magnitude larger. Hunting Bayou ranks first as the producer of the largest pollutant loads.

The load-runoff relations developed from several storm events can be extended in a useful way to estimate total annual loads for selected pollutants. A measured or predicted annual streamflow hydrograph is required along with average low-flow concentration values. During storm events, the load-runoff relation is used to predict the mass flow, while during intermittent low flows, mass flow is estimated by the product of stream-

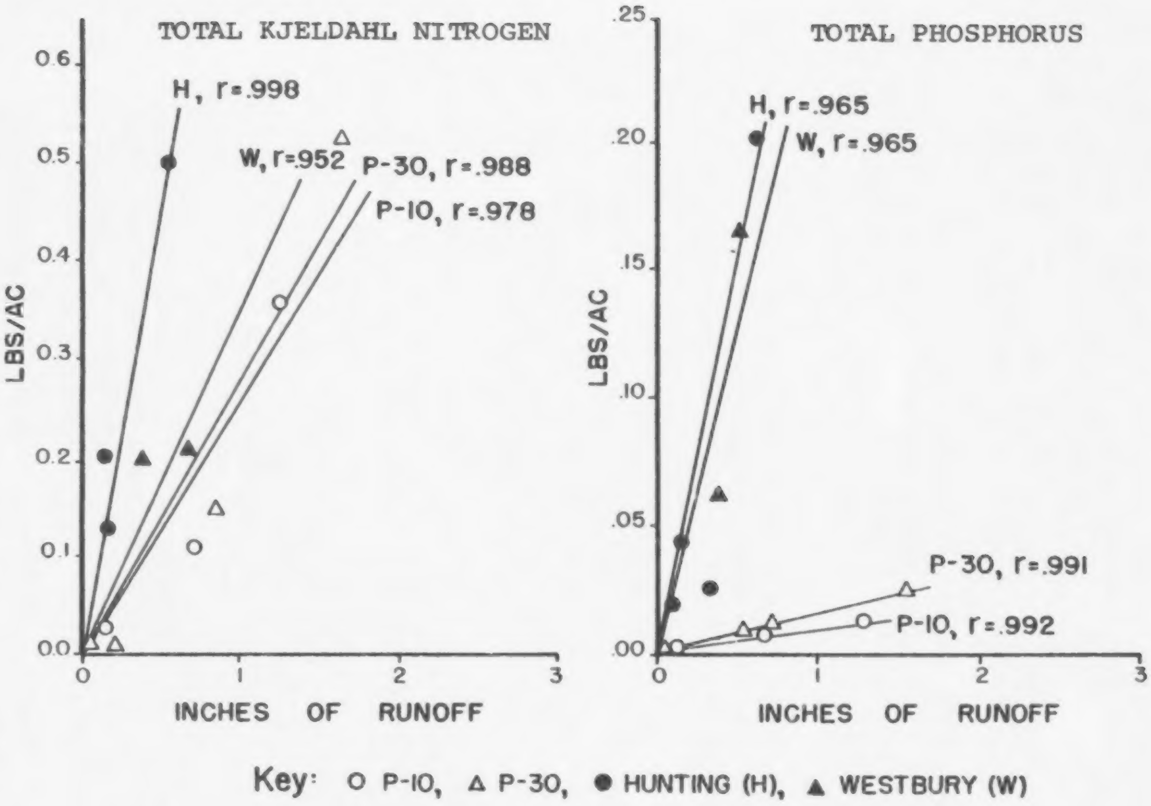


Figure 17. Load-runoff relationships for TKN and TP.

1 lb = .454 kg
1 ac = .405 ha
1 in = 2.54 cm

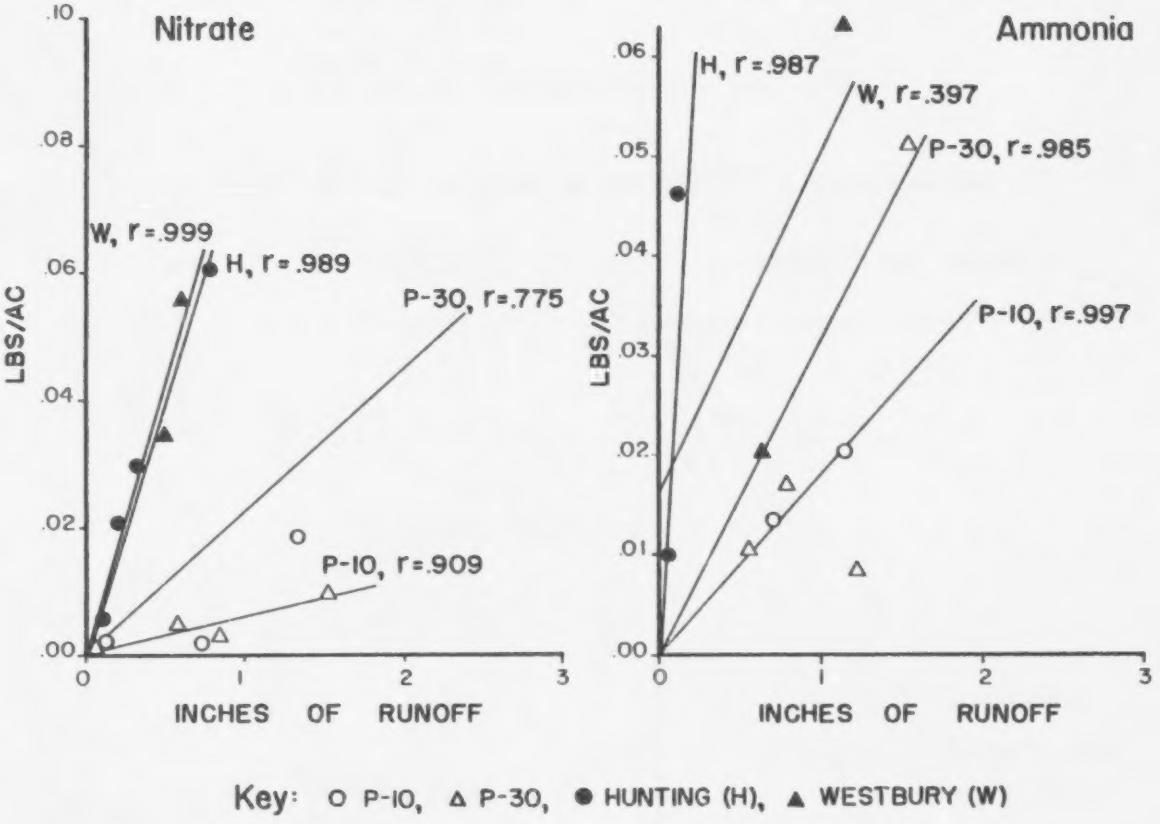


Figure 18. Load-runoff relationships for NO_3 and NH_3.

1 lb = .454 kg
1 ac = .405 ha
1 in = 2.54 cm

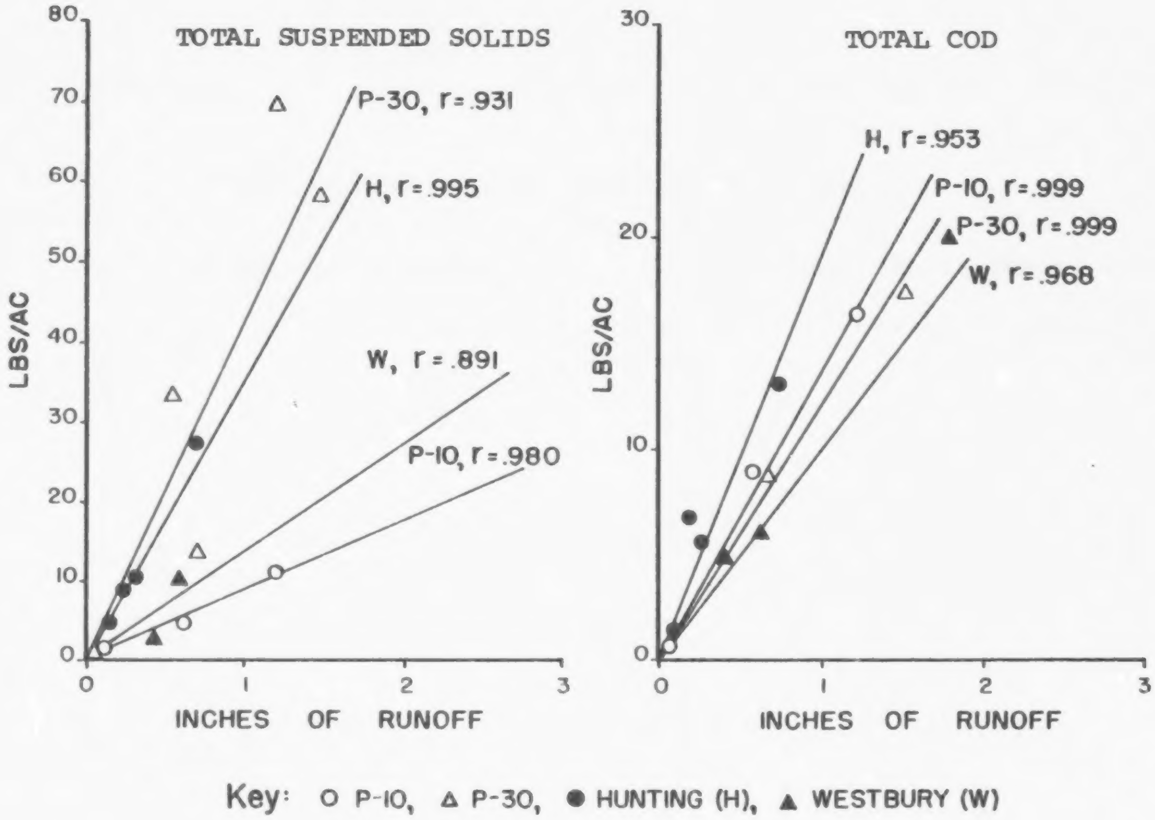


Figure 19. Load-runoff relationships for TSS. and total COD.
1 lb = .454 kg
1 ac = .405 ha
1 in = 2.54 cm

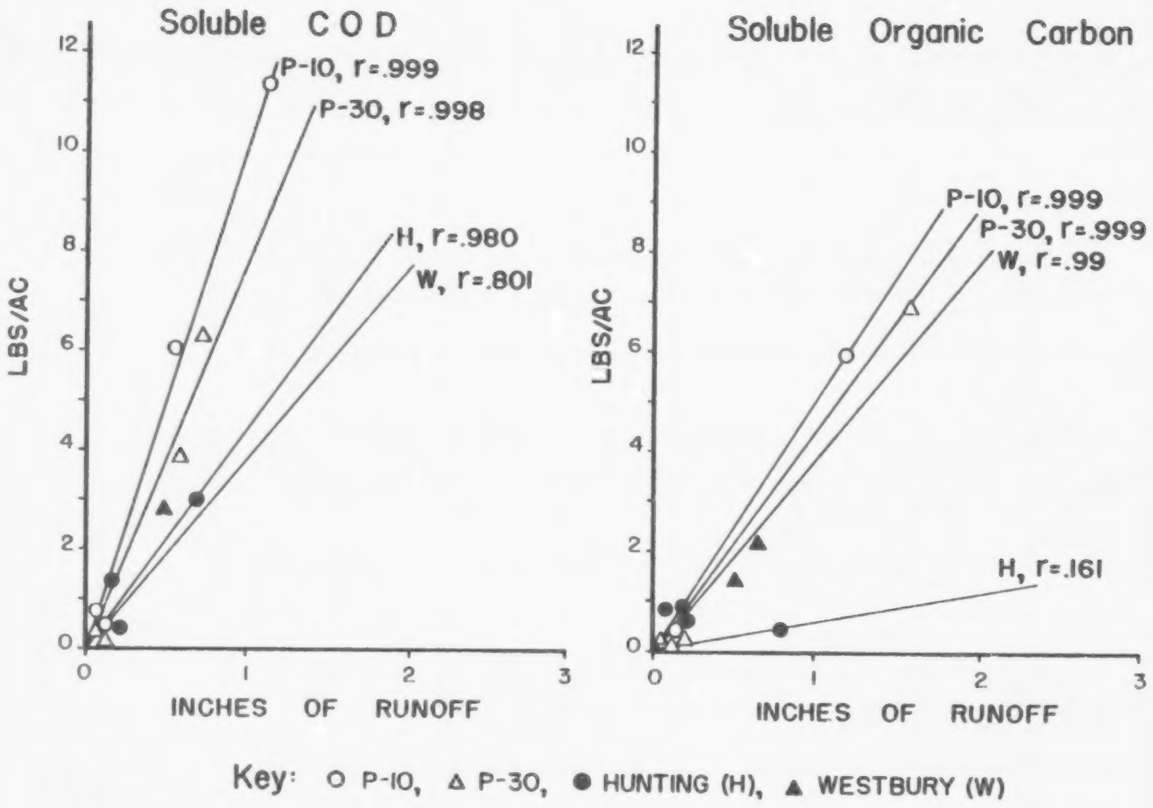


Figure 20. Load-runoff relationships for soluble COD and SOC.

1 lb = .454 kg
1 ac = .405 ha
1 in = 2.54 cm

TABLE 20. POLLUTANT LOAD RANKING OF THE FOUR STUDY AREA WATERSHEDS

		RANK			
		1	2	3	4
SS	Area	P30	HB	WB	P10
	Upper CL*	61.59	42.30	88.02	10.16
	1" Value	43.48	37.73	13.66	8.19
	Lower CL	25.36	33.15	-60.70	6.21
TCOD	Area	HB	P10	P30	WB
	Upper Cl	25.62	14.13	12.72	33.13
	1" Value	18.88	13.50	12.09	9.48
	Lower CL	12.14	12.87	11.46	-14.17
SCOD	Area	P10	P30	HB	WB
	Upper CL	10.01	9.27	6.64	31.56
	1" Value	9.86	8.76	4.44	4.06
	Lower CL	9.70	8.25	2.24	-23.45
SOC	Area	P10	P30	WB	HB
	Upper CL	5.045	4.78	4.48	2.64
	1" Value	5.00	4.54	3.75	0.70
	Lower CL	4.95	4.30	2.66	-1.25
NO_3	Area	WB	HB	P30	P10
	Upper CL	0.12	0.10	0.038	0.020
	1" Value	0.088	0.087	0.020	0.012
	Lower CL	0.057	0.072	0.0031	0.0051
NH_3	Area	HB	WB	P30	P10
	Upper CL	0.58	1.28	0.037	0.020
	1" Value	0.48	0.069	0.031	0.018
	Lower CL	0.38	-1.14	0.025	0.016
TKN	Area	HB	WB	P30	P10
	Upper CL	1.049	1.50	0.36	0.38
	1" Value	0.95	0.40	0.30	0.28
	Lower CL	0.85	-0.76	0.24	0.18
TP	Area	HB	WB	P30	P10
	Upper CL	0.40	0.90	0.028	0.017
	1" Value	0.28	0.24	0.021	0.014
	Lower CL	0.16	-0.43	0.014	0.011

* 95% Confidence Level. All confidence levels are for mean regression values at 1 inch of runoff. All loads are in lbs/acre.

P30 = Woodlands P30 Watershed
P10 = Woodlands P10 Watershed
HB = Hunting Bayou Watershed
WB = Westbury Watershed

Note: 1 in = 2.54 cm
1 lb/ac = 1.12 kg/ha

flow and concentration.

A comparison of annual loads for TSS, TP, NO_3 and total COD is shown in Table 21 for the P-10 forested site and P-30 urbanizing site at The Woodlands. The developed load-runoff relations were used to calculate the storm generated mass flows. The urbanizing watershed appears to be contributing greater loads of TSS on an annual basis compared to the forested site.

The procedure allows direct comparison of storm generated pollutant loads from non-point sources with the low-flow contributions, which are primarily of point source origin. Consequently, non-point loads can be quantitatively determined as a function of land use patterns as more storm data becomes available from other urbanizing watersheds.

The annual TSS load calculation can be used in conjunction with the U.S. Geological Survey grab sample method to calculate annual sediment loads. Relative accuracy of the two techniques remains undetermined.

Effects of Land Development on Runoff Quality--

Stormwater quality monitored at site P-10 represents runoff from a forested, undeveloped watershed and accordingly serves as a baseline for assessing changes due to urbanization. The P-30 sampling site located 6.8 miles (11 km) below P-10 monitors runoff from an additional 5,500 acres (2250 ha) which includes construction activity of The Woodlands Development Corporation. A comparison of these two sites during storm event #10 illustrates the effects of construction activity on runoff quality.

Heavy rainfall over the Panther Branch watershed on April 8, 1975 produced large amounts of runoff sampled at P-10 and P-30. Precipitation associated with the storm event began shortly after midnight on April 8, 1975 and continued till noon the same day. The storm featured 3 periods of intense rainfall at 4:30, 8:30 and 10:00 A.M. with interposing pauses or drizzle. The area rain gages measured 2.00, 2.65, 3.42 and 3.97 inches (5.08, 6.73, 8.69 and 10.08 cm) of rainfall, upper to lower watershed gages respectively, with the Theissen adjusted rainfall calculated to be 2.43 in (6.17 cm) on the P-10 watershed and 2.76 in (2.01 cm) on the P-30 watershed. Average rainfall intensity was 0.76 in/hr (1.93 cm/hr) and antecedent soil moisture conditions were dry with no rain recorded 7 days prior to the storm and 2.5 in (6.35 cm) the preceding month. Watershed runoff began after midnight April 8 and ended three days later. As shown below, the volume of runoff observed at site P-30 was greater than P-10 but peak discharge was essentially the same.

TABLE 21. ANNUAL MASS LOADS FROM P-10 AND P-30 WATERSHEDS. (October 1974 - September 1975)

	P-10 Watershed				P-10 and P-30 Watersheds Combined				
Month	TSS lbs x 10^5	TP lbs x 10^2	NO_3 lbs x 10^2	COD lbs x 10^4	TSS lbs x 10^5	TP lbs x 10^2	NO_3 lbs x 10^2	COD lbs x 10^4	No. Storms
Oct. '74	0.483	0.80	0.96	8.85	6.18	2.32	1.92	18.8	1
Nov.	6.27	6.84	7.71	88.89	43.56	15.66	15.92	123.5	4
Dec.	3.71	4.16	4.42	54.46	26.84	12.02	8.79	81.1	4
Jan.	1.12	1.32	2.14	47.38	5.26	5.04	2.40	21.1	4
Feb.	2.18	2.61	5.21	30.71	17.22	6.50	5.70	55.0	1
Mar.	1.05	2.65	1.68	13.20	6.84	3.92	2.45	18.8	2
Apr.	4.42	7.54	7.78	65.67	37.40	14.16	12.10	117.8	3
May	1.42	1.66	2.46	29.18	8.00	4.12	4.81	27.8	4
June	0.59	2.59	8.21	5.68	1.06	1.40	0.62	6.1	2
July	0.17	0.14	0.23	3.25	0.46	1.30	0.37	3.9	0
Aug.	0.08	0.065	0.068	1.50	0.26	0.77	0.21	2.2	0
Sept.'75	0.01	0.005	0.006	0.13	0.027	0.08	0.022	0.2	0
Total Load	21.50	30.38	40.87	348.91	154.10	67.35	55.37	476.3	25
	P-10 Watershed				P-30 Less P-10 Watershed				
Total Load (lbs/ac)	134	0.189	0.255	217	2387	0.665	0.261	229	

1 lb = .454 kg

	Streamflow Volume		Runoff		Peak Flow		Runoff
Site	acre-ft.	(ha-m)	in.	(cm)	cfs	(m^3/s)	Coeff.
P-10	1614	(199)	1.2	(3.05)	1170	(33.1)	50%
P-30	2829	(349)	1.57	(3.99)	1100	(31.1)	57%

The greater runoff volume for P-30, almost twice that of P-10, was a result of three factors: (1) larger drainage area, (2) heavier rainfall in the lower basin, and (3) impervious areas in The Woodlands development.

Figures 21 and 22 compare P-10 and P-30 pollutographs for TSS, total COD, TP and TKN. Hydrographs are also presented in the figures for flow rate and time references. Pollutograph analysis should consider the following:

1. Those areas of The Woodlands developed or under construction encompassed only 10% of the total watershed. The majority of stormwater runoff originated in undeveloped forest lands.

2. Developed or construction areas were located adjacent to P-30, as shown in Figure 23. As a result, runoff originating in these areas was observed early in the storm event.

The pollutographs indicate high TSS loads at P-30 (Figure 21), a result of sediments washed from easily eroded construction sites. Although the developing area comprised 10% of the watershed, it contributed as much as 80% of the TSS load at P-30. Total COD (Figure 21) exhibited a "first flush" at P-30, probably due to associated high TSS. The major portion (70%) of the total COD was soluble. Significant increases in TKN and TP at P-30 resulted from wash off of ammoniated phosphate and urea based fertilizers applied to the golf course in the developing area (Figure 22).

Development within the Panther Branch watershed has resulted in stormwater runoff quality changes. TSS and nutrients have increased although no significant change has been observed for oxygen demand. Results for storm event #10 are summarized in Table 22.

STORMWATER QUALITY MODELING

Several techniques are available for the prediction of water quality responses in a watershed. The SWMM model has been adapted for natural drainage conditions at The Woodlands in an effort to simulate stormwater quality response. The model operates from a relation between runoff rate and pollutant load, but the prediction of hydrographs has been more successful than pol-

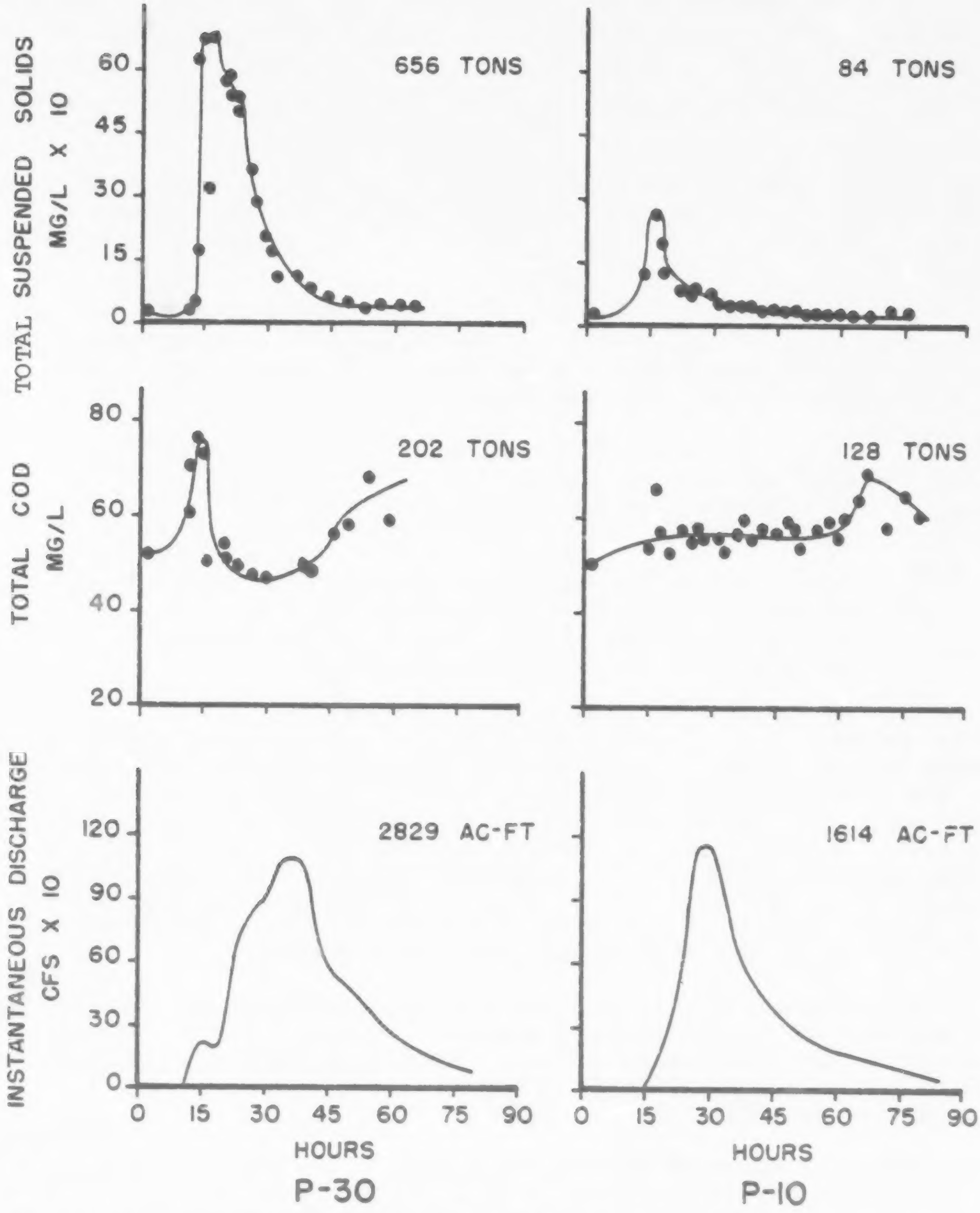


Figure 21. Comparison of P-10 and P-30 temporal distribution of streamflow, TSS and total COD for the storm event of April 8, 1975. 1 cfs = .028 m^3/sec; 1 ton = 907.2 kg; 1 ac-ft = .124 ha-m.

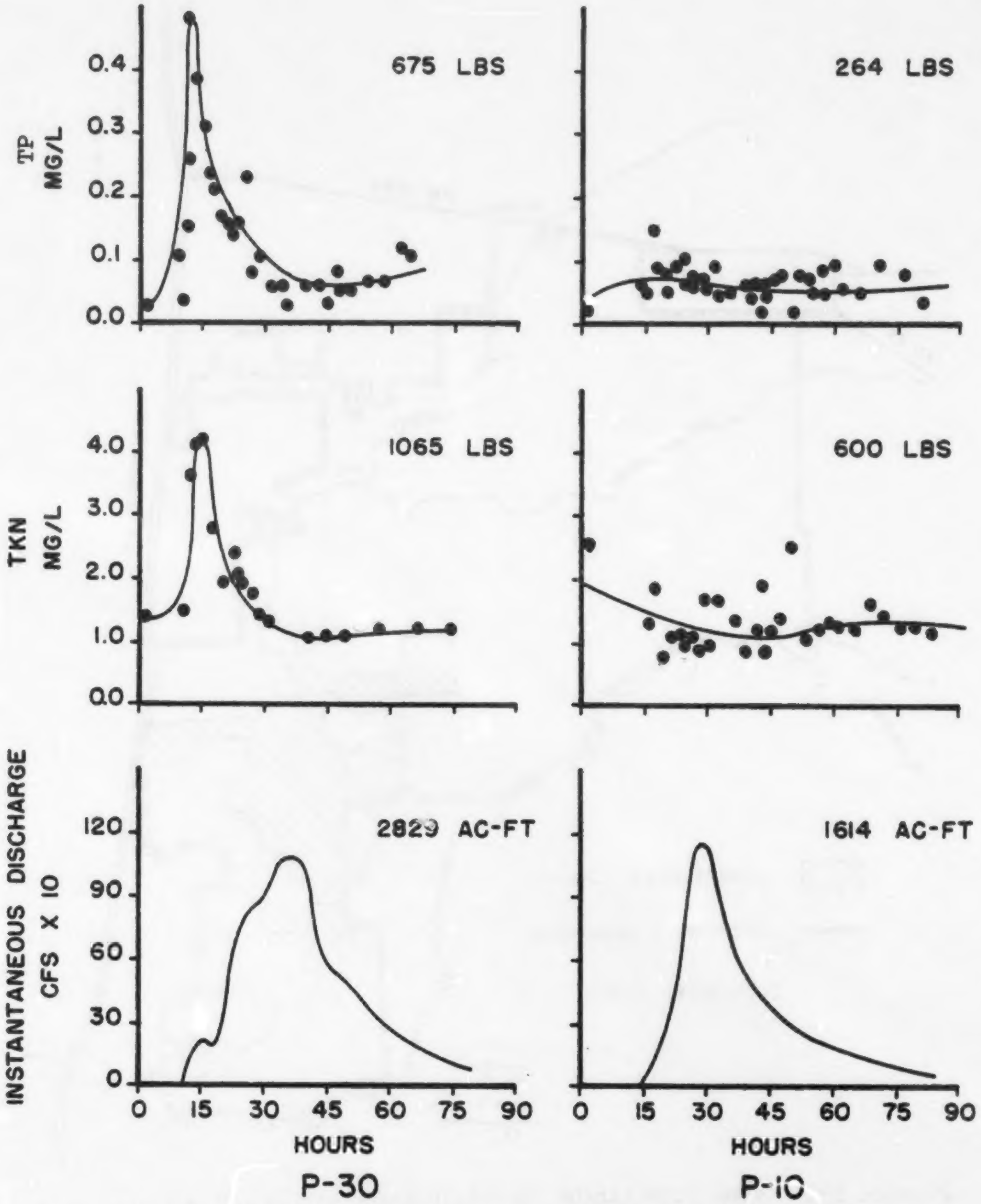
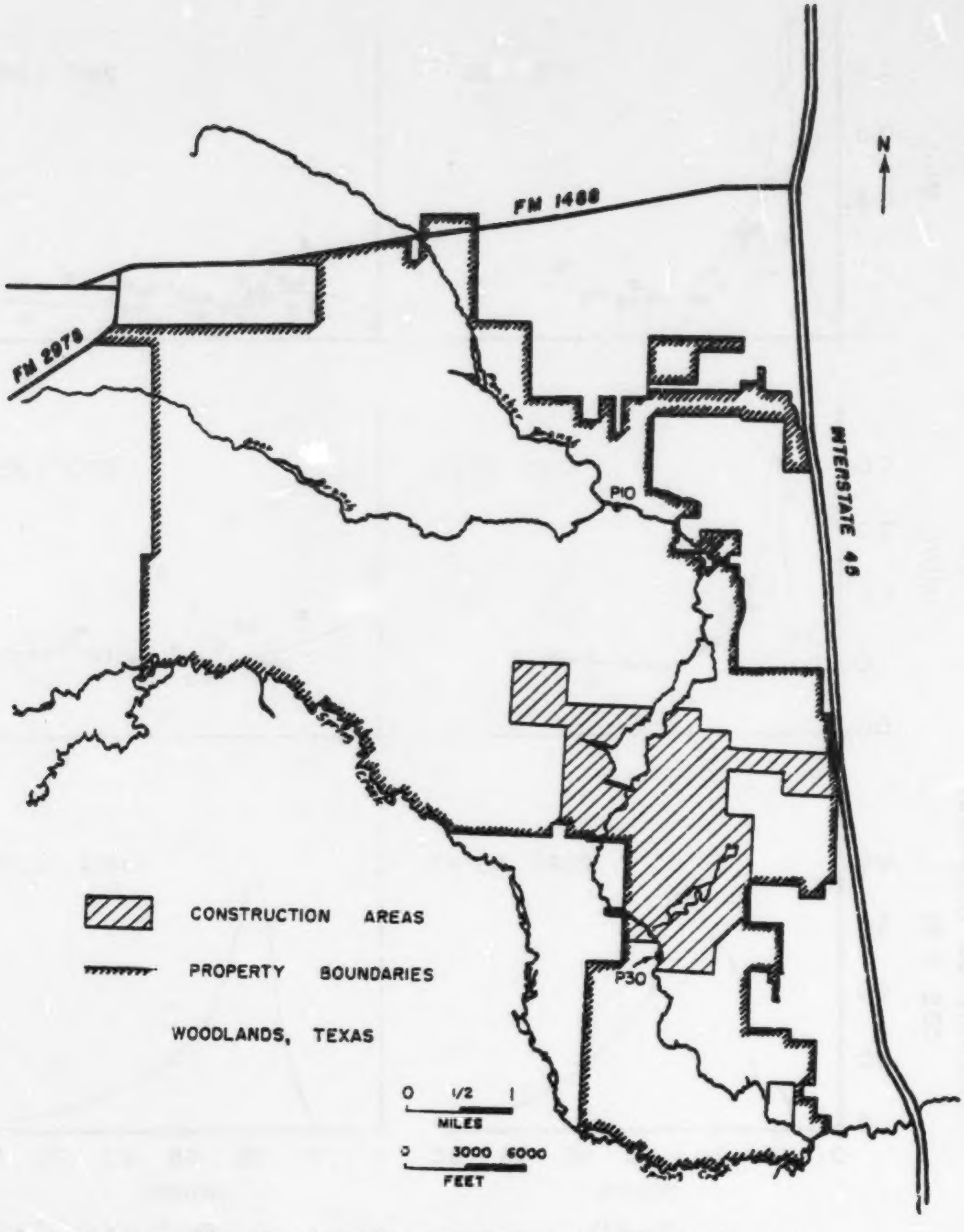


Figure 22. Comparison of P-10 and P-30 temporal distribution of streamflow, TP and TKN for the storm event of April 8, 1975. 1 lb = .454 kg; 1 cfs = .028 m^3/sec; 1 ac-ft = .124 ha-m.



FM 1488
FM 2978
INTERSTATE 45
N
P10
P30
CONSTRUCTION AREAS
PROPERTY BOUNDARIES
WOODLANDS, TEXAS
0 1/2 1
MILES
0 3000 6000
FEET

Figure 23. The Woodlands construction activity in relation to the P-10 and P-30 sampling sites.
1 mi = 1.6 km
1 ft = .305 m

TABLE 22. COMPARISON OF STORMWATER QUALITY AT P-10, P-30 AND DEVELOPING AREAS DURING STORM #10

	Forest with Development P-30	Forest P-10	The Woodlands Development (P-30) - (P-10)
Drainage Area (acres)	21,606	16,050	5,556
(ha)	8,750	6,500	2,250
Streamflow Volume (ac-ft)	2,829	1,614	1,215
(ha-m)	349	199	150
Average Concentration of Water Quality Parameters (mg/l)			
Ortho-phosphate	0.011	0.003	0.021
Total phosphorous	0.088	0.06	0.125
Ammonia	0.15	0.08	0.244
Nitrite	0.009	0.004	0.017
Nitrate	0.154	0.065	0.272
Total Kjeldahl Nitrogen	1.39	1.37	1.41
Total Suspended Solids	171	38.5	347
Soluble Organic Carbon	20.4	22	18.2
Total COD	52.6	58.7	44.5
Soluble COD	38.8	43	33.2

lutant response. The water quality procedure in the model is not designed to simulate the response from natural drainage, and has been updated for The Woodlands. New relationships between cumulative load (lbs) and cumulative runoff volume (ft^3) have been incorporated into SWMM for various parameters at The Woodlands. In this way, concentrations can be predicted as a function of runoff (22).

Pollutant Load Modeling for Multiple Events

The load-runoff relationships presented previously(Figures 17-20) provide the foundation for an uncomplicated, yet satisfactory, model for runoff pollutant load simulation of multiple or individual storm events. Given time increment values for runoff, the model consults time-varying load-runoff relationships to calculate mass flows during storm events.

Variation in the average pollutant concentration over time is approximated by variation of the load-runoff line slopes (Figures 17-20). These slopes represent the ratio of mass/time and volume/time, or mass/volume which is an average pollutant quality concentration for each watershed. Initially three parameters are defined for each load-runoff relationship: the average slope, the initial slope, and a factor which sets the range within which the slope can vary. The average slope can be roughly determined from the cumulative relationship produced from field data. The initial slope value depends primarily on initial conditions, and the range variable is determined by the spread in observed pollutant concentrations.

During dry periods the slopes are incrementally increased up to but not above the pre-defined maximum. This corresponds to the buildup of available pollutants on a watershed between storm events. An increment chosen to increase the slopes is required as input and is obtained primarily by trial and error. During a storm event the value of the slope decays exponentially by the same means employed in both the Storm Water Management Model (23) and the "Storm" model (24).

$$\begin{array}{l}\text{Lbs pollutant}\\ \text{washed off in}\\ \text{any time interval}\end{array} \propto \begin{array}{l}\text{Lbs}\\ \text{remaining on}\\ \text{the ground}\end{array}$$

or:

$$\frac{-dP}{dt} = kP \qquad (1)$$

which when integrated takes the form:

$$P_o - P = P_o \ (1 - e^{-kt}) \qquad (2)$$

Where $P_o - P$ = lbs washed away in time, t, and k is assumed to vary in direct proportion to the rate of runoff, r:

$$k = br \qquad (3)$$

b can be evaluated given the assumption that 0.5 in (1.3 cm) of runoff uniformly delivered in 1 hour washes away 90% of the pollutants (22). As a result the equation can be written:

$$P_o - P = P_o \ (1 - e^{-4.6\ rt}) \qquad (4)$$

The equation used to decay the load-runoff line slopes is:

$$\mathrm{PDS} = 1 - e^{-4.6\ rt} \ (\mathrm{PDS})_o \qquad (5)$$

Where PDS is the load-runoff curve slope at some point in time during the storm event and $(\mathrm{PDS})_o$ is the initial value.

A six month period of streamflow at site P-30 was chosen for sequential simulation. This period dating from October 28, 1974 to April 8, 1975 includes storm events 5, 7 and 10 monitored during the study. Storm events 8 and 9 were considered too small for use in the simulation. Predicted solids loads and the observed streamflow hydrographs are presented in Figure 24. Slope parameters used were derived from the load-runoff relationship, with the upper limit values found by trial and error.

Simulation results can be evaluated by comparing observed and simulated mass flows for individual storm events. As shown in Figure 25, the simulated curves compare satisfactorily to the observed mass flow curves. Table 23 gives comparisons of simulated to observed values for total pounds TSS, and peak magnitudes for each of the three storms.

Unit Loadograph for Single Event Simulation

The form of the stormwater mass flow curves, obtained from the product of instantaneous concentration and discharge, resemble the general shape of the streamflow hydrograph and provide a more useful measure of runoff loadings than the concentration curves. For a given watershed, it is possible to generate a unit hydrograph based on the incomplete gamma distribution. Using the theory of linear reservoirs, the resulting equation for the unit hydrograph becomes (25)

$$Q_n = \frac{S}{k\Gamma(n)} \left(\frac{t}{k}\right)^{n-1} \exp(-t/k) \qquad (6)$$

where S = total storage (one inch of runoff); k = constant; n = outflow from n^{th} reservoir. The watershed is considered as n serially arranged linear reservoirs, and it is possible to fit an observed hydrograph by varying k and n.

The theory of linear reservoirs can be extended for mass flow curves in order to develop a corresponding unit pollutograph or unit loadograph for application to urban storm runoff. In this way, mass flow curves can be generated in a similar fashion to the hydrograph by varying appropriate constants. The watershed is considered as n serially arranged tanks with first order decay, and the mass balance becomes

$$\frac{dM_1}{dt} = g_o - g_1 - k_1 M \qquad (7)$$

where M_1 = total mass; g_o = mass inflow; g_1 = mass outlfow; k_1 = linear decay coefficient. By solving the equation for n reservoirs in series, assuming outflow from one is inflow to the next, and assuming M = kg (analogous to S = kQ), the final resulting equation for the unit loadograph becomes

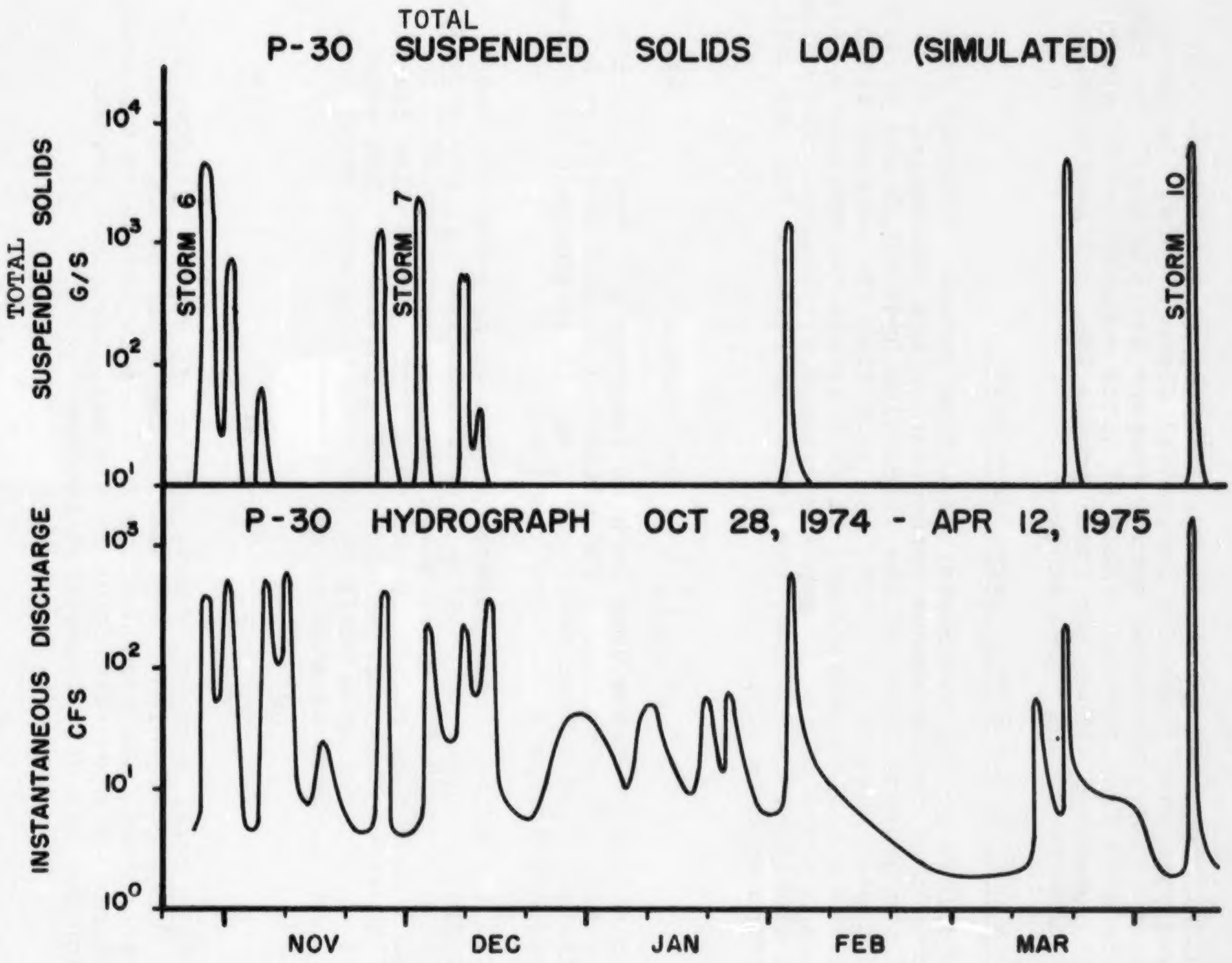


Figure 24. Hydrograph and predicted TSS load for the P-30 hydrograph period of 10/28/74 to 4/12/75.
1 cfs = .028 m^3/sec

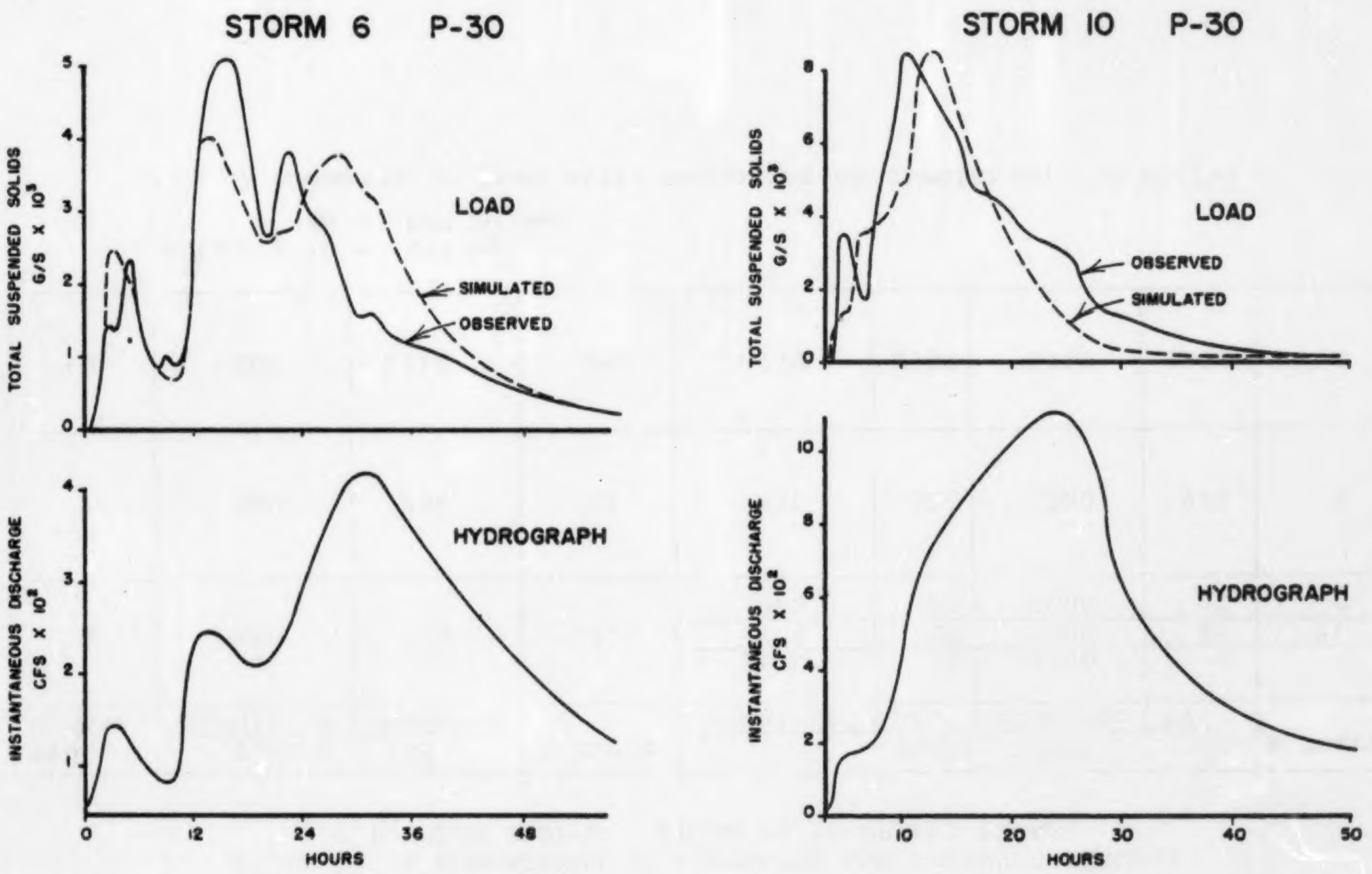


Figure 25. Hydrographs and observed and simulated mass flow curves for P-30 storm events.
1 cfs = .028 m^3/sec

TABLE 23. A COMPARISON OF SIMULATED AND OBSERVED RESULTS FOR THREE STORMS. STORM #6 IS TRIPLE PEAKED

Storm Number	Pounds x 10^3		% Error	Peaks g/sec				% Error
	Simulated	Observed		simulated	hr.[1]	observed	hr.[1]	
6	880	775	13.5	2600	3	2500	5	4
				4100	13	5200	15	21
				3900	27	3900	22	0
7	340	296	15	2350	926	2200	926	7
10	853	1312	35	8750	3907	8750	3906	0

note: 1 lb = .454 kg
1 cfs = .028 m^3/sec

1 hr is measured in time since beginning of simulation (10/28/74)

$$g_n = \frac{M}{K\Gamma(n)}\left(\frac{t}{k}\right)^{n-1} \exp(-a/t) \qquad (8)$$

The similarities of equation 8 and equation 6 are obvious, where g_n is mass flow (kg/sec), a equals $(1 + kk_1)/k$, and M is total mass.

Hydrograph and mass flow simulations for Storm #10 on the P-10 site are shown in Figure 26. The timing of the hydrograph peak and the total volume compare well, but the recession rate is predicted lower than the observed. The simulation of TSS and TP mass flow curves (g/sec) yielded similar results, with good peak and total mass definition, but a predicted recession rate lower than observed. This storm yielded 1.2 in (3.05 cm) of runoff, and the unit response (in inches) can be obtained by dividing all ordinates by 1.2.

The application of this approach is in a preliminary stage due to lack of significant storm runoff data (at least 1 in or 2.54 cm) on Hunting Bayou or The Woodlands watersheds. As more storm event data are collected from other watersheds in the area, it will be possible to investigate relationships between the gamma distribution shape parameters (n,k) and land use or physiographic factors in the watershed. In general, the time of peak of the unit loadograph is related to n and k by the equation

$$t_p = \frac{(n-1)k}{1+kk_1} \qquad (9)$$

Urbanizing watersheds should have lower values of n and k than undeveloped watersheds of the same size. As n is increased, k must be correspondingly decreased in order to yield the same t_p value for a given watershed.

The unit loadograph can be used in the same manner as the unit hydrograph. Once the unit response has been determined for a watershed, storms of varying intensity can be analyzed by lagging and superposition of the unit graphs. A unit pollutograph (concentration vs time) is found by dividing the ordinates of the unit loadograph by corresponding hydrograph flows. Because of the linear load-runoff relationships which have been developed, the linear assumption of unit response is further justified.

The unit loadograph approach suffers the same limitations as the unit hydrograph method with regard to assumptions of uniform rainfall and initial conditions, but it does offer a relatively simple and useful technique for analyzing stormwater pollution response as a function of land use, watershed characteristics, and hydrologic conditions.

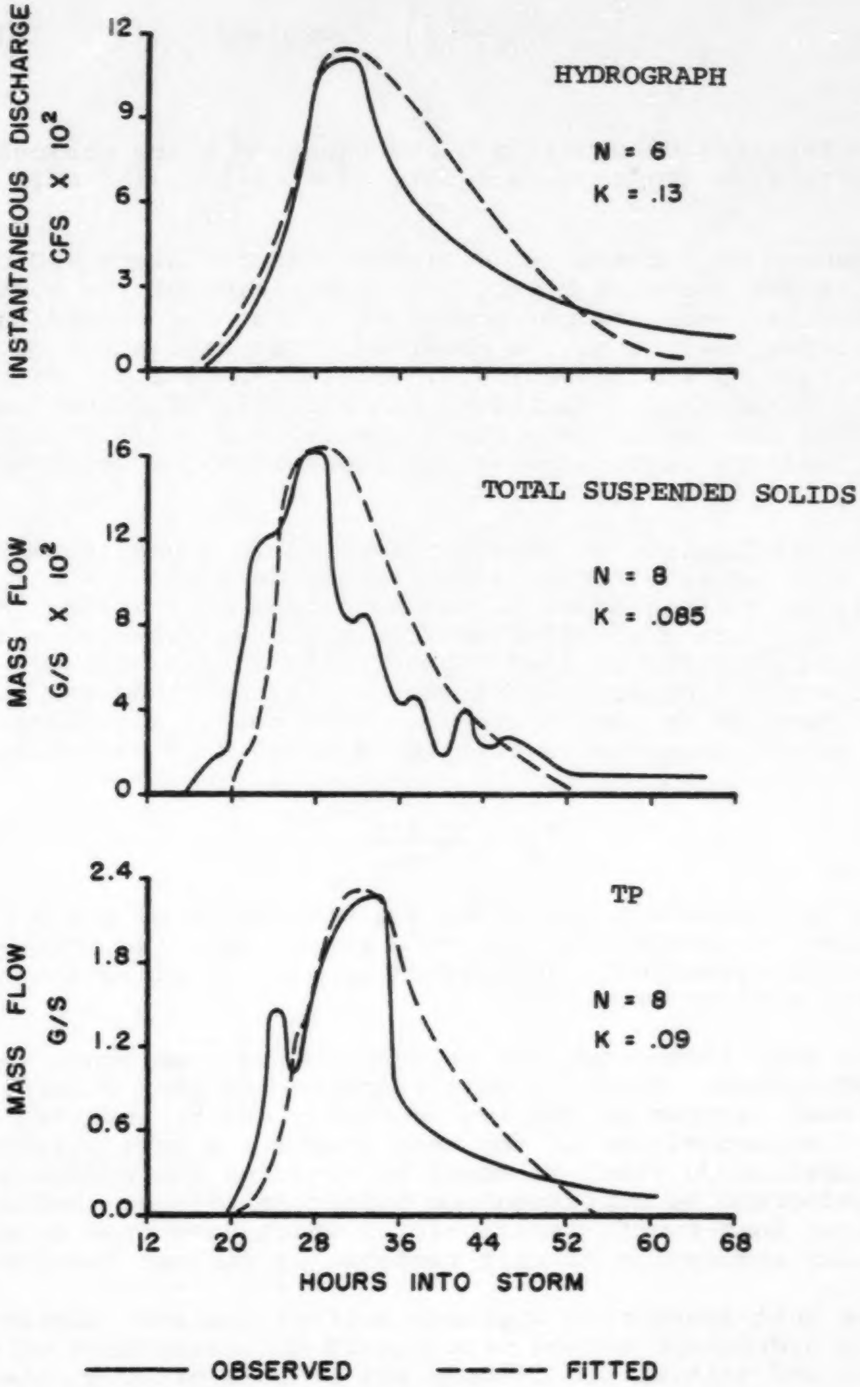


Figure 26. Fitted curves for storm runoff and pollutant mass flows observed at P-10 on 4/8/75. 1 cfs = .028 m^3/sec

STORMWATER TREATMENT AT THE WOODLANDS LAKES

Water Quality Needs

Irrigation--

Collected stormwaters are to be used for golf course irrigation at The Woodlands to supplement natural precipitation. The critical water quality parameter for irrigation is salinity. Excessive salinity affects plants by increasing osmotic pressure in the soil which limits uptake of water by plants. However, this is not the case at The Woodlands and, therefore, salinity will not be a problem. Electrical conductivity measurements in stormwater runoff is less than 3000 micromhos at The Woodlands and is "excellent to good for most plants" (26). The presence of nutrients in stormwaters slated for irrigation is not high and in this case considered an asset rather than a pollutant. High TSS concentration or large particulates could cause mechanical problems such as pump damage or clogging of sprinkler heads, but careful placement of the intake structure will avoid these difficulties. TSS concentration in Lake Harrison during low-flow conditions is about 100 mg/l and average particulate size is estimated at 5 microns or less. Average storm event TSS concentrations range between 25 and 250 mg/l, levels acceptable for pumping requirements. The velocity in the distribution system will keep the solids in suspension. Particulate size criteria will be set by the orifice size of the irrigation system.

Aesthetics--

The water quality level for aesthetics is presently met without any stormwater treatment. The lake is devoid of floating debris or objectionable odors and promises to support a wide variety of lifeforms. Superficially, it resembles early stages of other local man-made lakes. High nutrient levels may promote macrophyte growth and algal blooms, but macrophytes can be controlled by a regular lake maintenance program and algal blooms can be prevented by reducing the lake detention times and nutrient levels (21).

Recreation--

In a discussion of recreational water uses, two divisions must be considered: contact and noncontact. The water quality requirement for contact recreation, which involves substantial risk of ingestion, is more stringent than that of noncontact (27). Swimming is the primary example of contact recreation and is prohibited in The Woodlands' lakes.

A water quality criteria designed strictly for boating would be similar to that for aesthetics, with the added requirement for fecal coliform levels. It is recommended that fecal coliform levels of 2000/100 ml average and 4000/100 ml maximum be observed for "unofficial recreation" waters. Levels of 1000/100 ml average and 2000/100 ml maximum were suggested for official noncontact waters (28). Fishing water criteria invoke an additional requirement that harvested species be fit for human consumption. Edible fish species should be free of toxic chemicals and pathogenic bacteria or viruses. The data to determine the fulfillment of this requirement is not presently available. The consumption of fish from such waters has been practiced without harmful results. Coliforms in the digestive system of fish caught at Woodlands are in higher concentrations than from other lakes but presumably do not reach the edible portions (28).

Water Supply Uses--

Lake Harrison ranks as a poor raw drinking water source because it would require a high level of treatment before use (26). With groundwater, a less expensive and more reliable source is easily obtained. Its use for this function is to be restricted to emergencies.

THE LAKE SYSTEM

The man-made lakes at The Woodlands will serve as recreational centers, wildlife preserves and storage for stormwater runoff. The lakes will contribute to the maintenance of a perched water table necessary for plant life. The lake water will also be used for irrigation of adjacent golf courses. Inputs to the lake system are limited to stormwater runoff and treated wastewater from The Woodlands Wastewater Reclamation Plant with ultimate capacity of 6 mgd (.264 m^3/sec). For a year of average rainfall, treated wastewater will comprise 75% of the flow through the lake system. Design effluent quality for the plant is indicated in Table 20 and suggests that the lakes will contain clear waters with somewhat elevated nutrient concentrations as compared to existing surface waters. Lake detention time during dry weather will be approximately six days. Consequently, treated wastewater will be the dominant influence on lake water quality at The Woodlands.

The lakes will serve as stormwater storage reservoirs and, in so doing, will remove significant amounts of pollutants, primarily due to sedimentation.

Lake Harrison Sedimentation

Eight storm events were monitored at the lake system, ranging from 0.26 in. (0.66 cm) to 3.97 in. (10 cm) of rainfall. In the following paragraphs, the largest storm indicates the usefulness of reservoirs for preventing release of construction site sediment washoff.

Storm Event #10--

Rainfall associated with the storm event began shortly after midnight on April 8, 1975 and continued until noon the same day. An early morning cloudburst was followed after a four hour pause by less intense rainfall totaling 3.97 in. (10 cm). The hyetograph is shown in Figure 27. Runoff passing the Lake B gaging station, the major inflow to Lake Harrison, originated in a watershed undergoing intense development at this time. Much of the drainage system itself was being constructed under specifications of the "natural drainage" system including Lake C, 656 ft (200 m) upstream of Lake B. Lake C was constructed to serve as a wet weather pond and golf course water hazard. Unfortunately, its low earthen spillway had yet to be sodded and provided an erosion source within the drainage channel.

Lake Harrison inflow and outflow hydrographs are compared in Figure 28. Characteristic of runoff response in a small watershed, the multi-peaked inflow hydrograph was a product of the sporadic hyetograph (Figure 27). Intense stormwater flow deepened the inflow channel by 6 in. (15 cm) and obliterated bales of hay placed in the channel to act as flow control devices. Stormwater flow crested shortly before noon on April 8 at a record discharge of 123 cfs (3.48 m^3/s). Bank storage and ponding helped prolong minimum flow in the channel for two days, contributing to the total inflow runoff volume of 93 acre-ft (11.4 ha-m). The lake system effectively damped inflow fluctuations. The hydrograph peak traveled through the lakes in a half hour.

Stormwater quality--Table 24 compares flow weighted mean and maximum water quality concentrations for runoff sampled at Lake Harrison inflow and outflow. Since runoff volumes were roughly equivalent, a comparison of relative loadings is redundant to the comparison of mean concentrations. Greater values for o-PO_4 NH_3, NO_2 and NO_3 indicate the outflow was nutrient enriched as a result of one or a combination of two sources:

(1) Unmeasured runoff from the fertilized area adjacent to the lakes and/or direct precipitation on the lakes,

(2) The quality of water held in the lakes prior to the storm event. (Water impounded in the lake prior to the storm event approximated the runoff volume.)

Lake Harrison served as an equalization basin minimizing the difference between maximum and average parameter concentrations. A prominent flush corresponding to the first peak of the Lake B hydrograph was evident for most parameters at the inflow. For example, nitrate concentration at the flush, maximum value, was an order of magnitude greater than average concentration. This flush was not observed at Lake A and average concentrations approximated maximum concentrations.

Sediment removal--Superimposed on the lake hydrographs of Figure 28 are the TSS pollutographs. The reduction

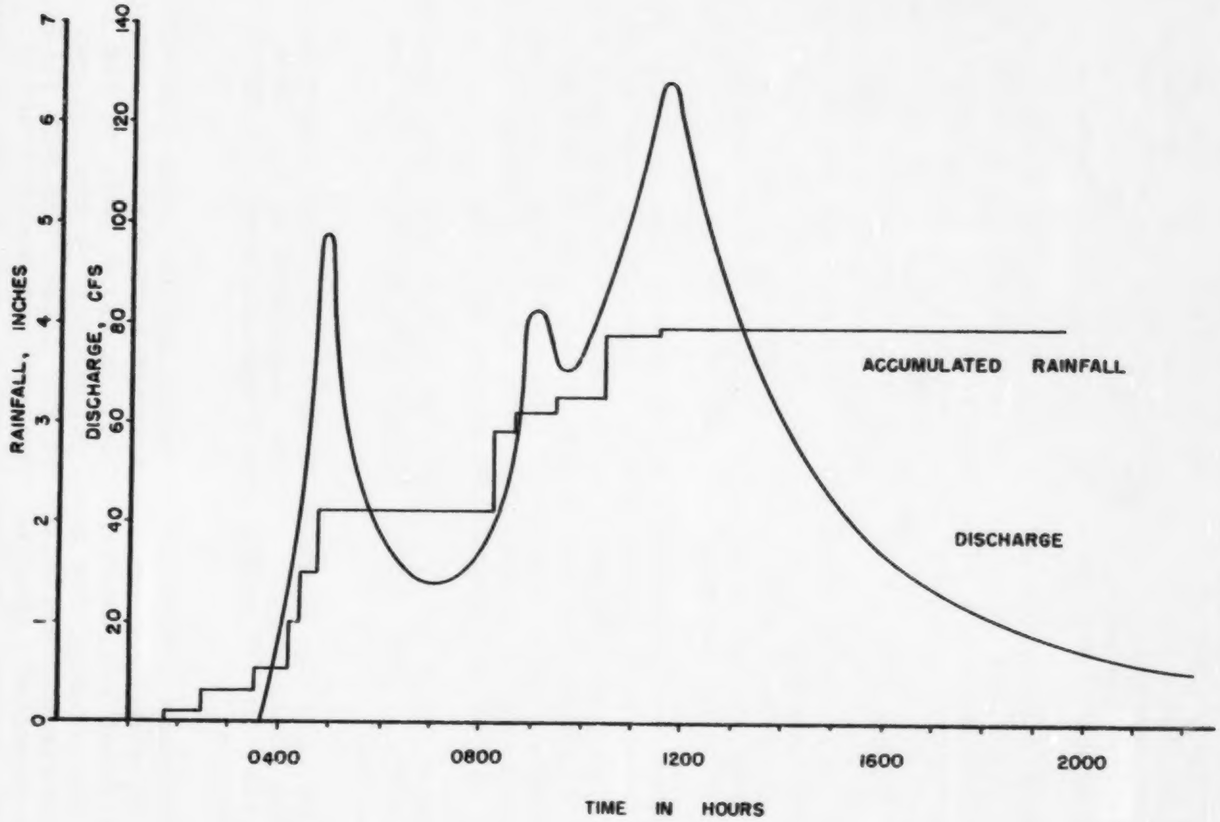


Figure 27. Hydrograph and cumulative hyetograph at the Lake B gauging station for the April 8, 1975 storm event.
1 in = 2.54 cm

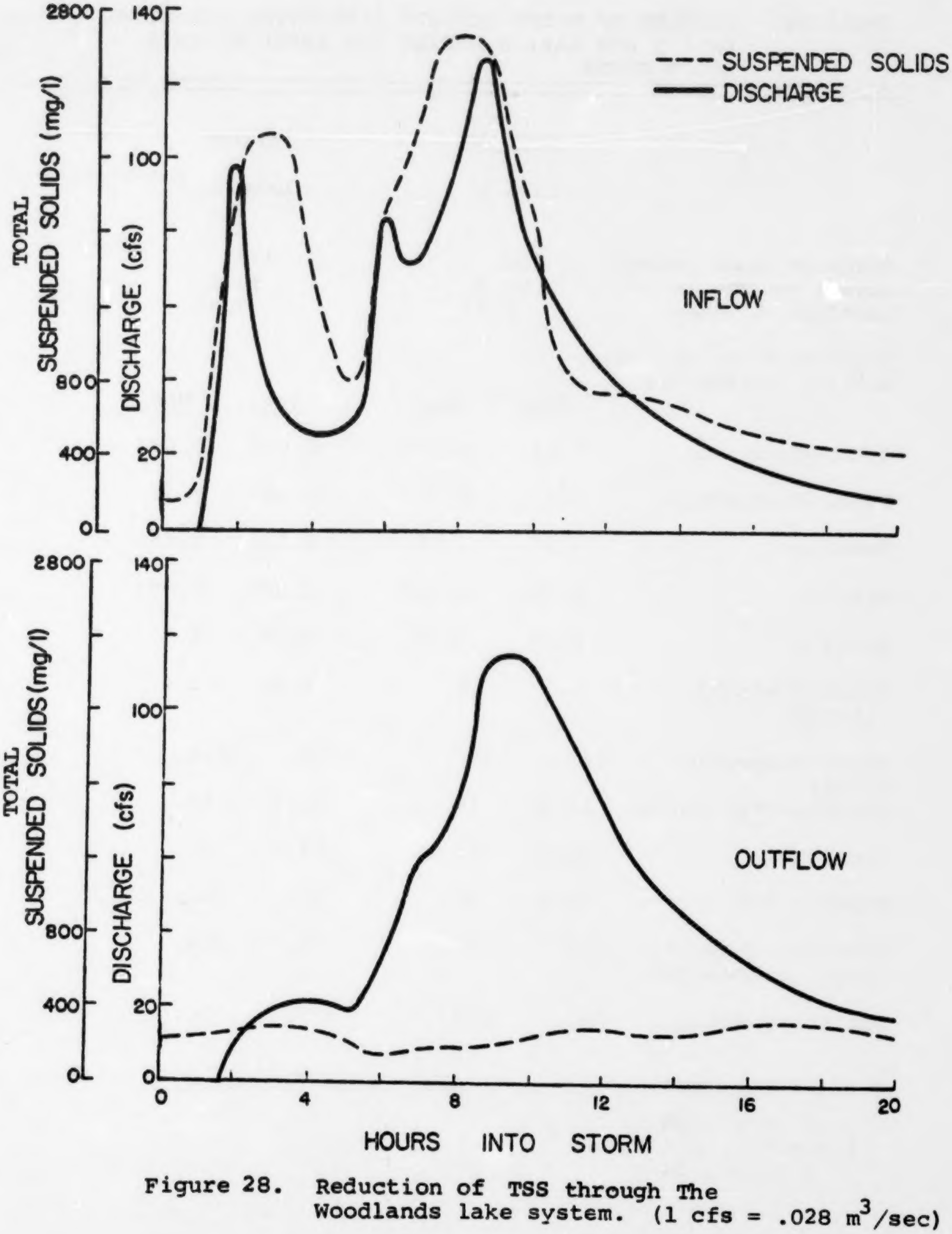


Figure 28. Reduction of TSS through The Woodlands lake system. (1 cfs = .028 m^3/sec)

TABLE 24. SUMMARY OF WATER QUALITY PARAMETERS FOR SITES LAKE A AND LAKE B DURING THE APRIL 8, 1975 STORM EVENT

	OUTFLOW Lake A		INFLOW Lake B	
Drainage Area (acres)	483		337	
Runoff Volume (ac-ft)	93.4		93.2	
Rainfall (inches)	3.97		3.97	
Concentration of Water Quality Parameters:*	Avg.	Max.	Avg.	Max.
Ortho-phosphate	0.015	0.048	0.005	0.013
Total Phosphorous	0.10	0.19	0.11	0.36
Ammonia	0.16	0.26	0.11	0.15
Nitrite	0.032	0.046	0.009	0.054
Nitrate	0.28	0.32	0.15	2.1
Total Kjeldahl Nitrogen	1.3	2.	1.86	3.1
Total Suspended Solids	245.	356.	1273.	2660.
Soluble Org. Carbon	13.6	19.	16.2	22.
Total COD	41.8	45	63.7	87.
Soluble COD	26.4	31.	32.	45.
Specific Conductance (micromhos)	130.	215.	85.	304.
Turbidity (JTU)	160.	210.	375.	900.

* all concentrations in mg/l except when indicated.

1 ac = .405 ha
1 ac-ft = .124 ha-m
1 in = 2.54 cm

of solids by sedimentation is a significant lake function desirable in stormwater management. The high TSS concentration of 2660 mg/l at inflow was reduced to 356 mg/l at outflow. Detention in Lake Harrison reduced the stormwater sediment load from 160 tons (145 t) to 31 tons (28 t), an 80% reduction in solids, storing 129 tons (117 t). This mass reduced the volume of the 110 acre-ft (13.6 ha-m) lake by less than 0.1% if 80 lb/ft^3 (1282 kg/m^3) is assumed. Erosion from the Lake B watershed was effectively prevented from entering Panther Branch by the lake system.

Table 25 shows the reduction in stormwater sediment load by Lake Harrison for all storms monitored. All but one storm event recorded over 80% solids removal. Complete removal, 100%, is a result of total stormwater storage by Lake Harrison and does not preclude discharge at a later time.

TABLE 25. STORMWATER SEDIMENT REMOVAL AT LAKE HARRISON

	Total Suspended Solids Load During Storm Event		
Storm #	lbs[1] Input (Lake B)	lbs Discharged (Lake A)	% Load Reduction
8	104	Flow stored within lake	100%
9	13800	991	93%
10	322000	61900	80%
13	6700	Flow stored	100%
14	11530[2]	1850	84%
15 & 16	4840	3270	32%

[1] 1 lb = .454 kg

[2] Estimated value (Lake B gage inoperative) calculated using estimated 10.1 ac-ft (1.25 ha-m) inflow times sample average concentration, 421 mg/l.

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